US009381645B1

(12) **United States Patent**
Yarlagadda et al.

(10) **Patent No.: US 9,381,645 B1**
(45) **Date of Patent: Jul. 5, 2016**

(54) **SYSTEM FOR AUTOMATING MANIPULATION OF ITEMS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/563,609**

(22) Filed: **Dec. 8, 2014**

(51) **Int. Cl.**
G06K 15/00 (2006.01)
B25J 9/16 (2006.01)

(52) **U.S. Cl.**
CPC ***B25J 9/1697*** (2013.01)

(58) **Field of Classification Search**
USPC 235/383, 381, 375; 700/245, 247; 705/27.1
See application file for complete search history.

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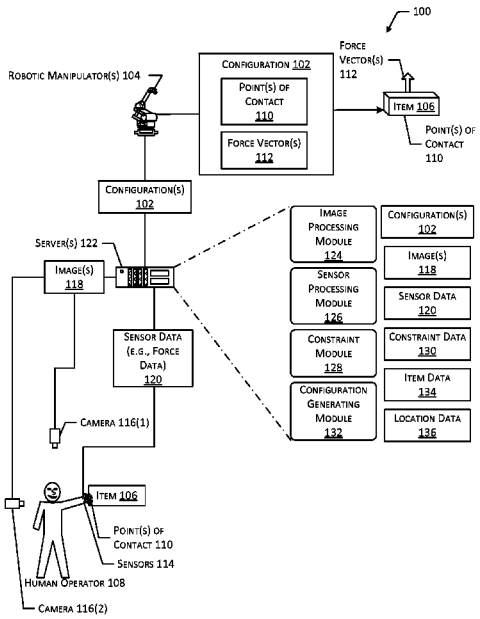
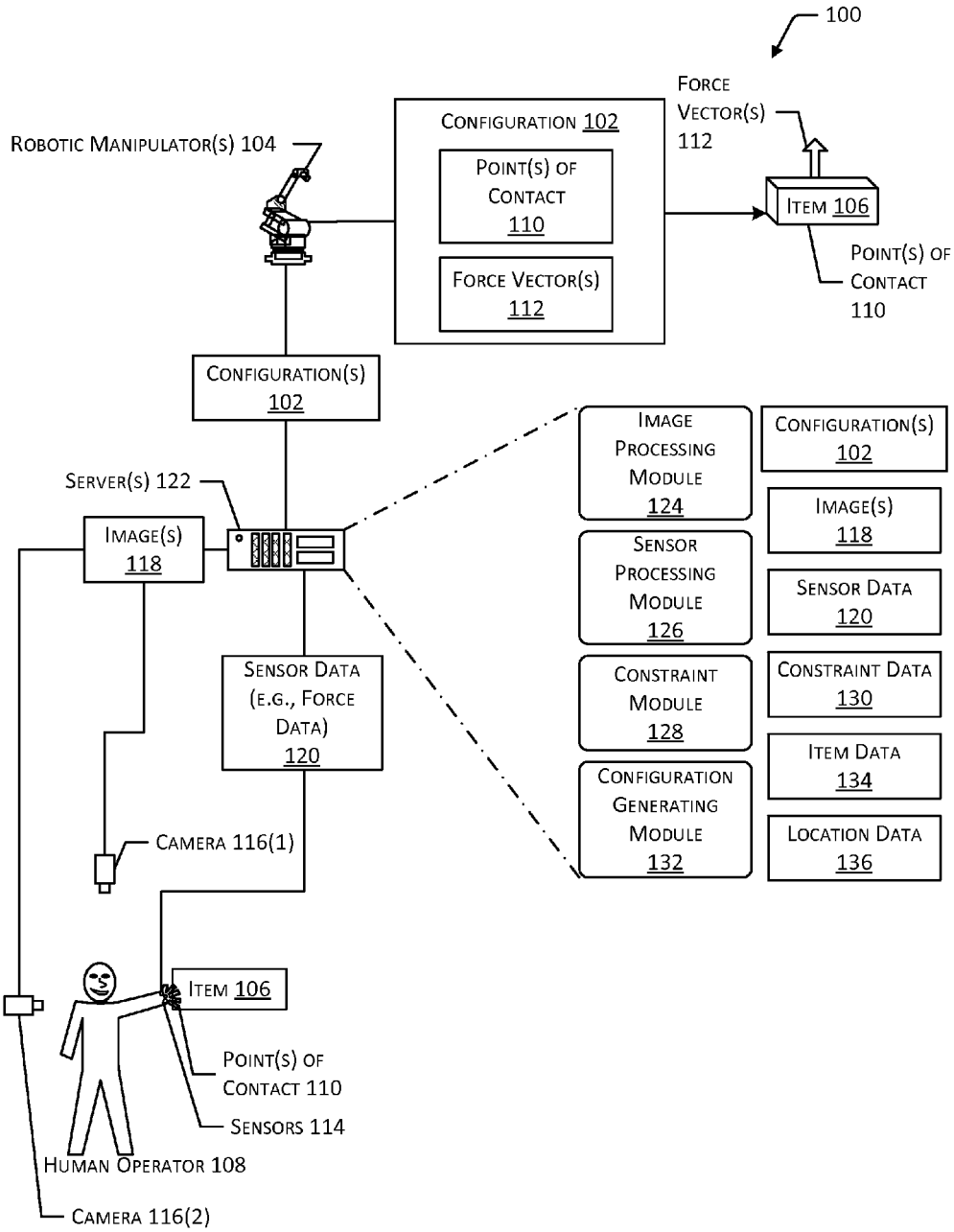
(57) **ABSTRACT**

Described are techniques for storing and retrieving items using a robotic manipulator. Images depicting a human interacting with an item, sensor data from sensors instrumenting the human or item, data regarding physical characteristics of the item, and constraint data relating to the robotic manipulator may be used to generate one or more configurations for the robotic manipulator. Points of contact and force vectors of the configurations may correspond to the points of contact and force vectors determined from the images and sensor data.

20 Claims, 8 Drawing Sheets

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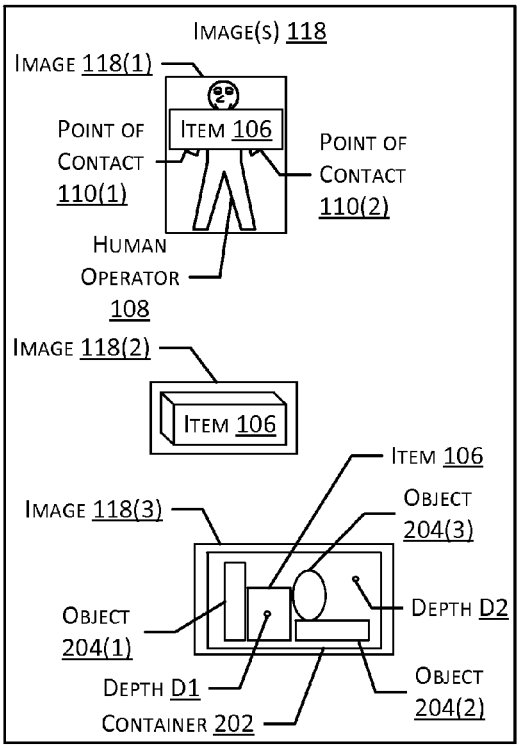
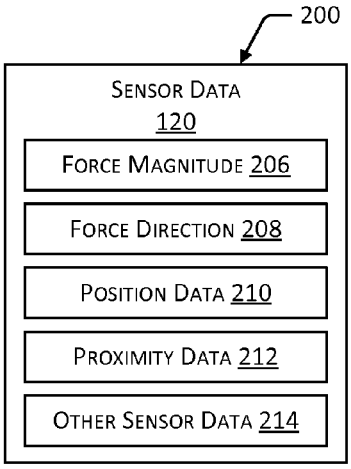
Force Vector(s) 112
Configuration 102
Point(s) of Contact 110
Force Vector(s) 112
Robotic Manipulator(s) 104
Item 106
Point(s) of Contact 110
Configuration(s) 102
Server(s) 122
Image(s) 118
Sensor Data (e.g., Force Data) 120
Image Processing Module 124
Sensor Processing Module 126
Constraint Module 128
Configuration Generating Module 132
Configuration(s) 102
Image(s) 118
Sensor Data 120
Constraint Data 130
Item Data 134
Location Data 136
Camera 116(1)
Item 106
Point(s) of Contact 110
Sensors 114
Human Operator 108
Camera 116(2)

FIG. 1


IMAGE(S) 118
IMAGE 118(1)
ITEM 106
POINT OF CONTACT 110(1)
POINT OF CONTACT 110(2)
HUMAN OPERATOR 108
IMAGE 118(2)
ITEM 106
ITEM 106
IMAGE 118(3)
OBJECT 204(3)
DEPTH D2
OBJECT 204(1)
DEPTH D1
OBJECT 204(2)
CONTAINER 202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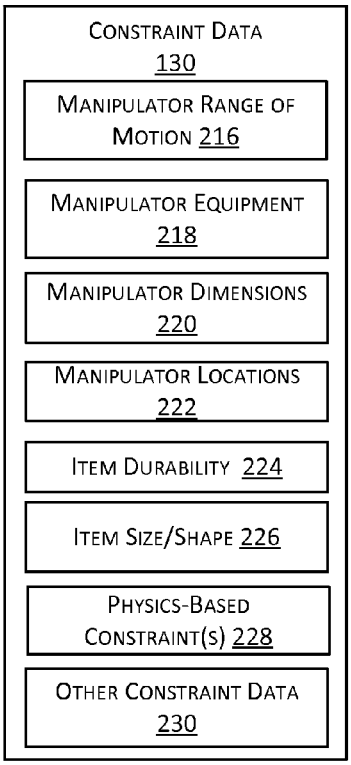
FORCE MAGNITUDE 206
FORCE DIRECTION 208
POSITION DATA 210
PROXIMITY DATA 212
OTHER SENSOR DATA 214


CONSTRAINT DATA 130
MANIPULATOR RANGE OF MOTION 216
MANIPULATOR EQUIPMENT 218
MANIPULATOR DIMENSIONS 220
MANIPULATOR LOCATIONS 222
ITEM DURABILITY 224
ITEM SIZE/SHAPE 226
PHYSICS-BASED CONSTRAINT(S) 228
OTHER CONSTRAINT DATA 230

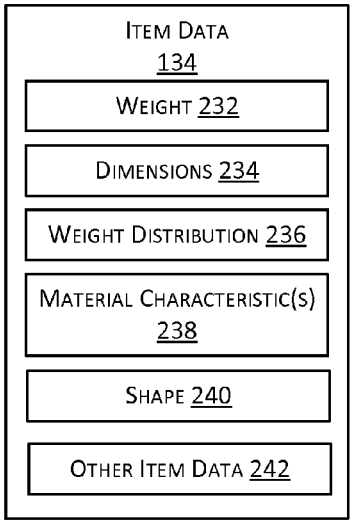

ITEM DATA 134
WEIGHT 232
DIMENSIONS 234
WEIGHT DISTRIBUTION 236
MATERIAL CHARACTERISTIC(S) 238
SHAPE 240
OTHER ITEM DATA 242

FIG. 2

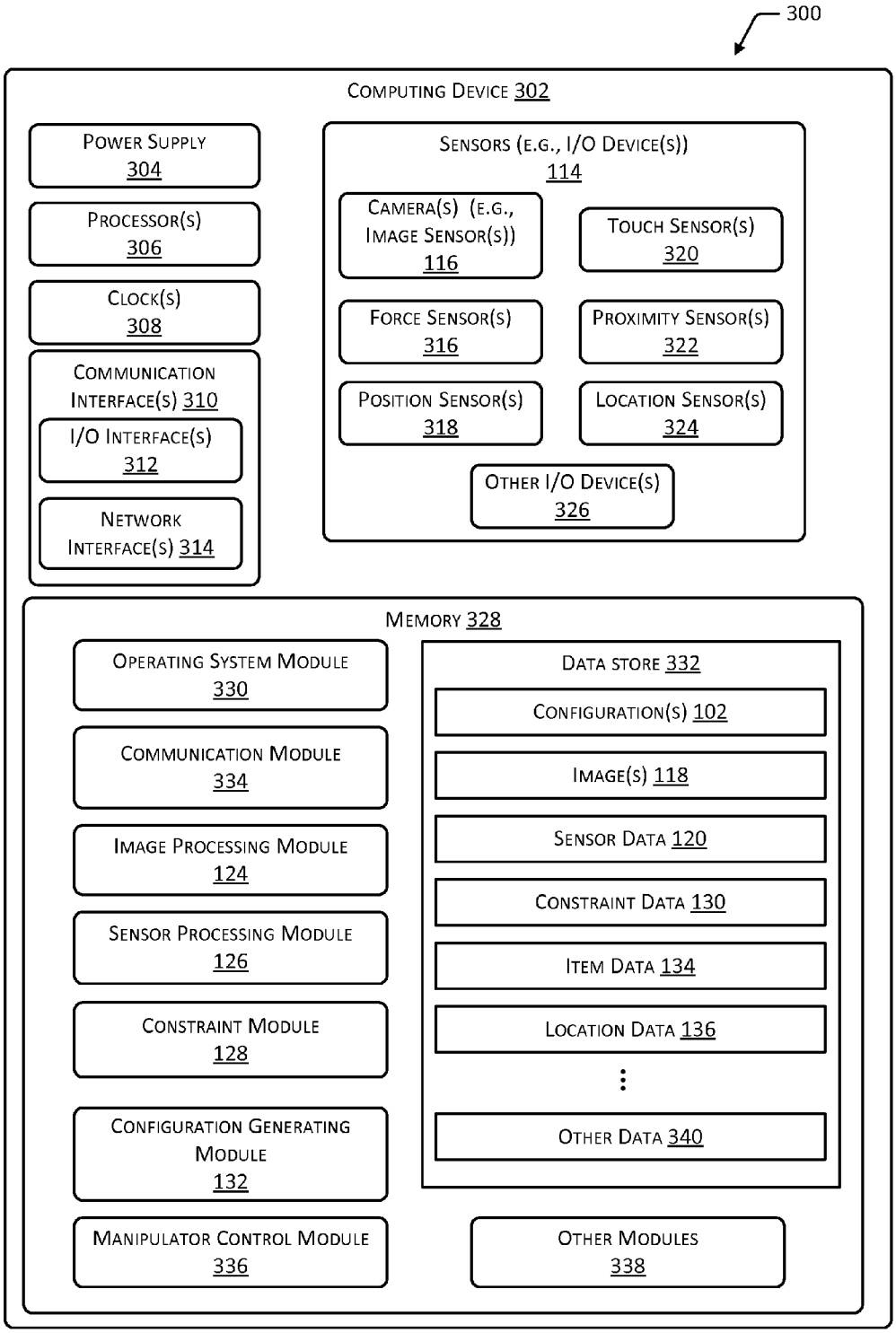

300
COMPUTING DEVICE 302
POWER SUPPLY 304
PROCESSOR(S) 306
CLOCK(S) 308
COMMUNICATION INTERFACE(S) 310
I/O INTERFACE(S) 312
NETWORK INTERFACE(S) 314
SENSORS (E.G., I/O DEVICE(S)) 114
CAMERA(S) (E.G., IMAGE SENSOR(S)) 116
TOUCH SENSOR(S) 320
FORCE SENSOR(S) 316
PROXIMITY SENSOR(S) 322
POSITION SENSOR(S) 318
LOCATION SENSOR(S) 324
OTHER I/O DEVICE(S) 326
MEMORY 328
OPERATING SYSTEM MODULE 330
COMMUNICATION MODULE 334
IMAGE PROCESSING MODULE 124
SENSOR PROCESSING MODULE 126
CONSTRAINT MODULE 128
CONFIGURATION GENERATING MODULE 132
MANIPULATOR CONTROL MODULE 336
DATA STORE 332
CONFIGURATION(S) 102
IMAGE(S) 118
SENSOR DATA 120
CONSTRAINT DATA 130
ITEM DATA 134
LOCATION DATA 136
OTHER DATA 340
OTHER MODULES 338

FIG. 3

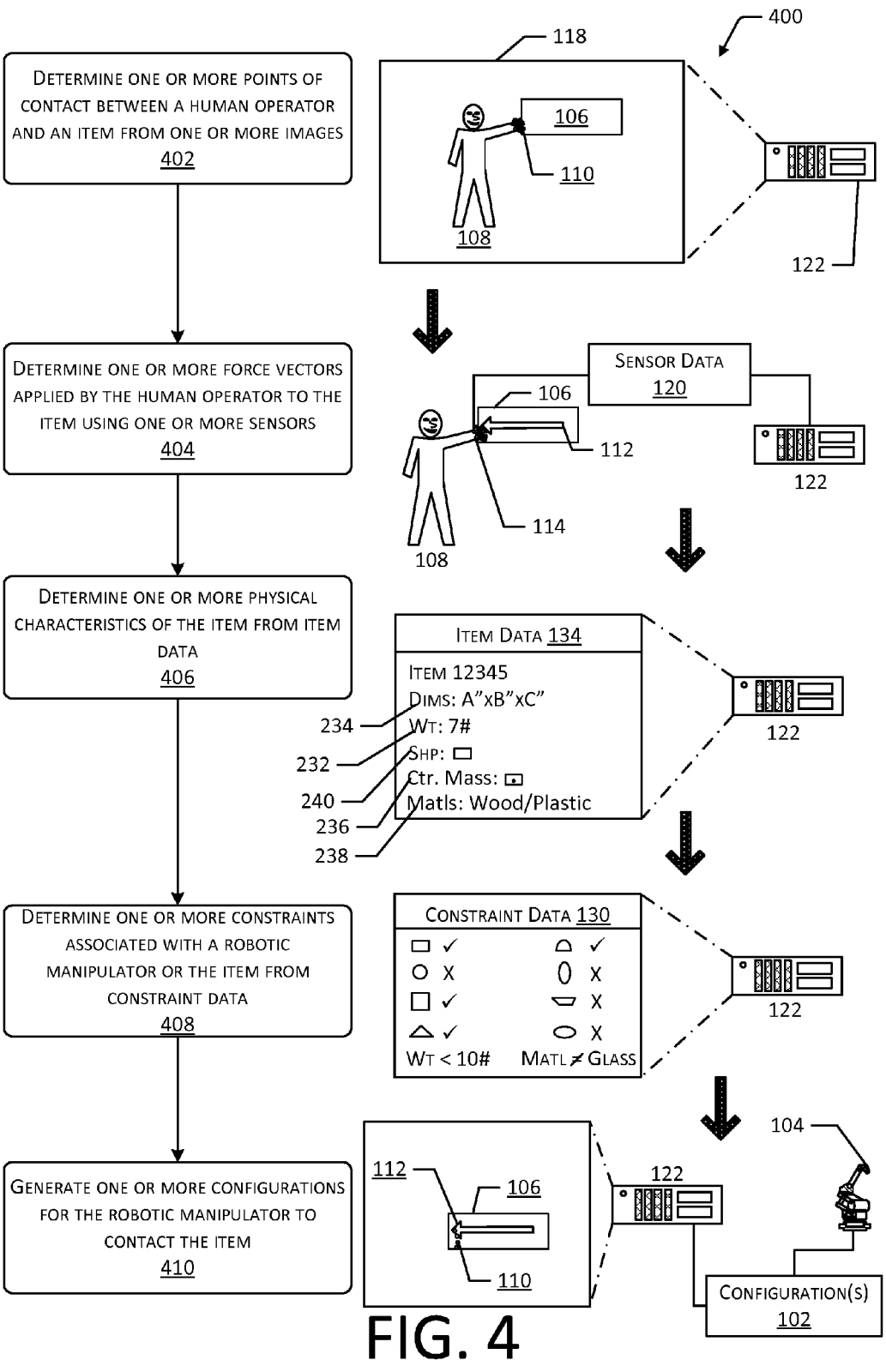

DETERMINE ONE OR MORE POINTS OF CONTACT BETWEEN A HUMAN OPERATOR AND AN ITEM FROM ONE OR MORE IMAGES 402
DETERMINE ONE OR MORE FORCE VECTORS APPLIED BY THE HUMAN OPERATOR TO THE ITEM USING ONE OR MORE SENSORS 404
DETERMINE ONE OR MORE PHYSICAL CHARACTERISTICS OF THE ITEM FROM ITEM DATA 406
DETERMINE ONE OR MORE CONSTRAINTS ASSOCIATED WITH A ROBOTIC MANIPULATOR OR THE ITEM FROM CONSTRAINT DATA 408
GENERATE ONE OR MORE CONFIGURATIONS FOR THE ROBOTIC MANIPULATOR TO CONTACT THE ITEM 410
400
118
106
110
108
122
SENSOR DATA 120
106
112
114
108
122
ITEM DATA 134
ITEM 12345
DIMS: A"xB"xC"
WT: 7#
SHP:
Ctr. Mass:
Matls: Wood/Plastic
234
232
240
236
238
122
CONSTRAINT DATA 130
WT < 10#
MATL ≠ GLASS
122
112
106
110
122
104
CONFIGURATION(S) 102

FIG. 4

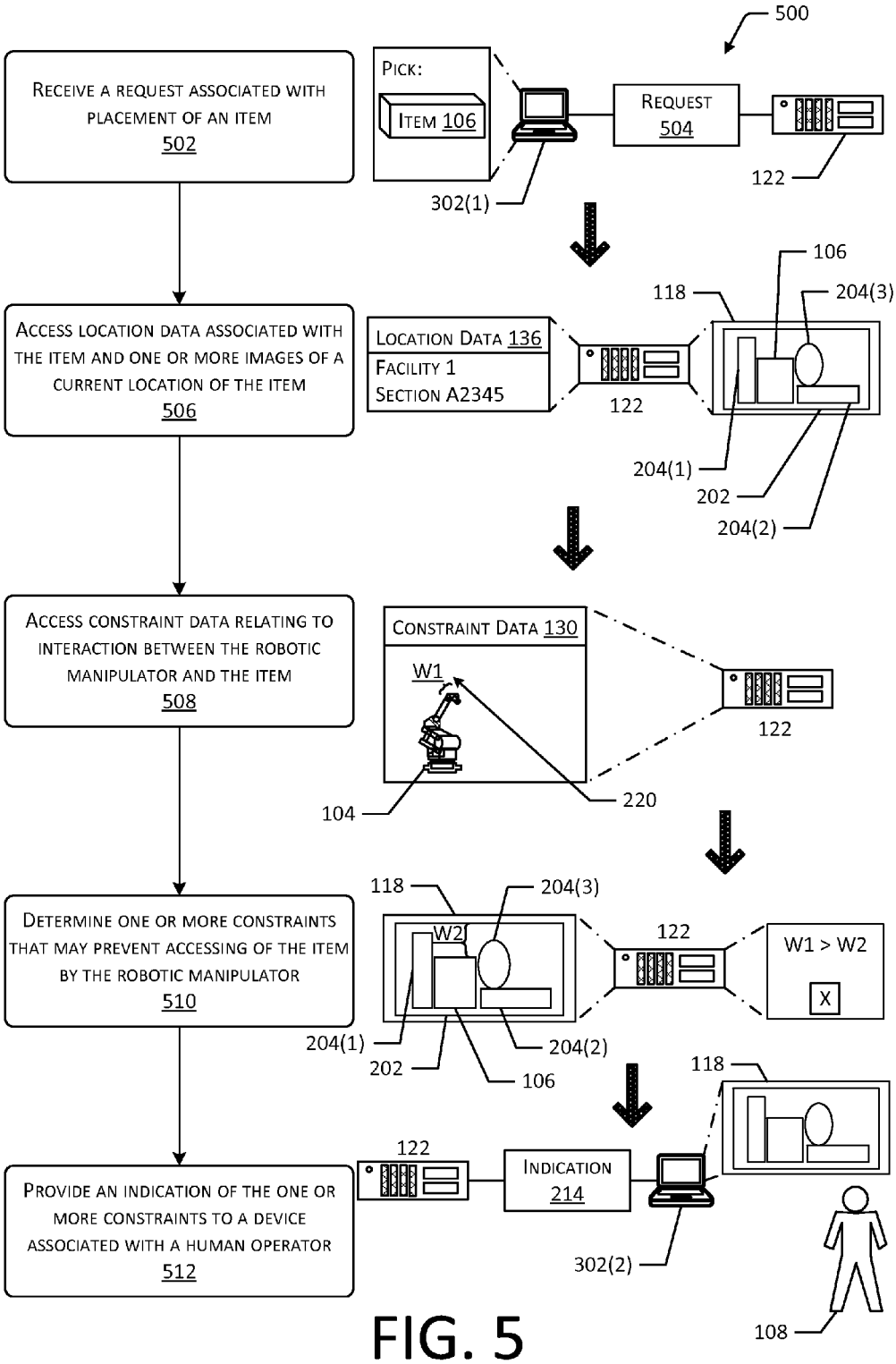

500
RECEIVE A REQUEST ASSOCIATED WITH PLACEMENT OF AN ITEM 502
PICK:
ITEM 106
REQUEST 504
122
302(1)
ACCESS LOCATION DATA ASSOCIATED WITH THE ITEM AND ONE OR MORE IMAGES OF A CURRENT LOCATION OF THE ITEM 506
LOCATION DATA 136
FACILITY 1
SECTION A2345
106
118
204(3)
122
204(1)
202
204(2)
ACCESS CONSTRAINT DATA RELATING TO INTERACTION BETWEEN THE ROBOTIC MANIPULATOR AND THE ITEM 508
CONSTRAINT DATA 130
W1
122
104
220
DETERMINE ONE OR MORE CONSTRAINTS THAT MAY PREVENT ACCESSING OF THE ITEM BY THE ROBOTIC MANIPULATOR 510
118
204(3)
W2
122
W1 > W2
X
204(1)
202
106
204(2)
PROVIDE AN INDICATION OF THE ONE OR MORE CONSTRAINTS TO A DEVICE ASSOCIATED WITH A HUMAN OPERATOR 512
118
122
INDICATION 214
302(2)
108

FIG. 5

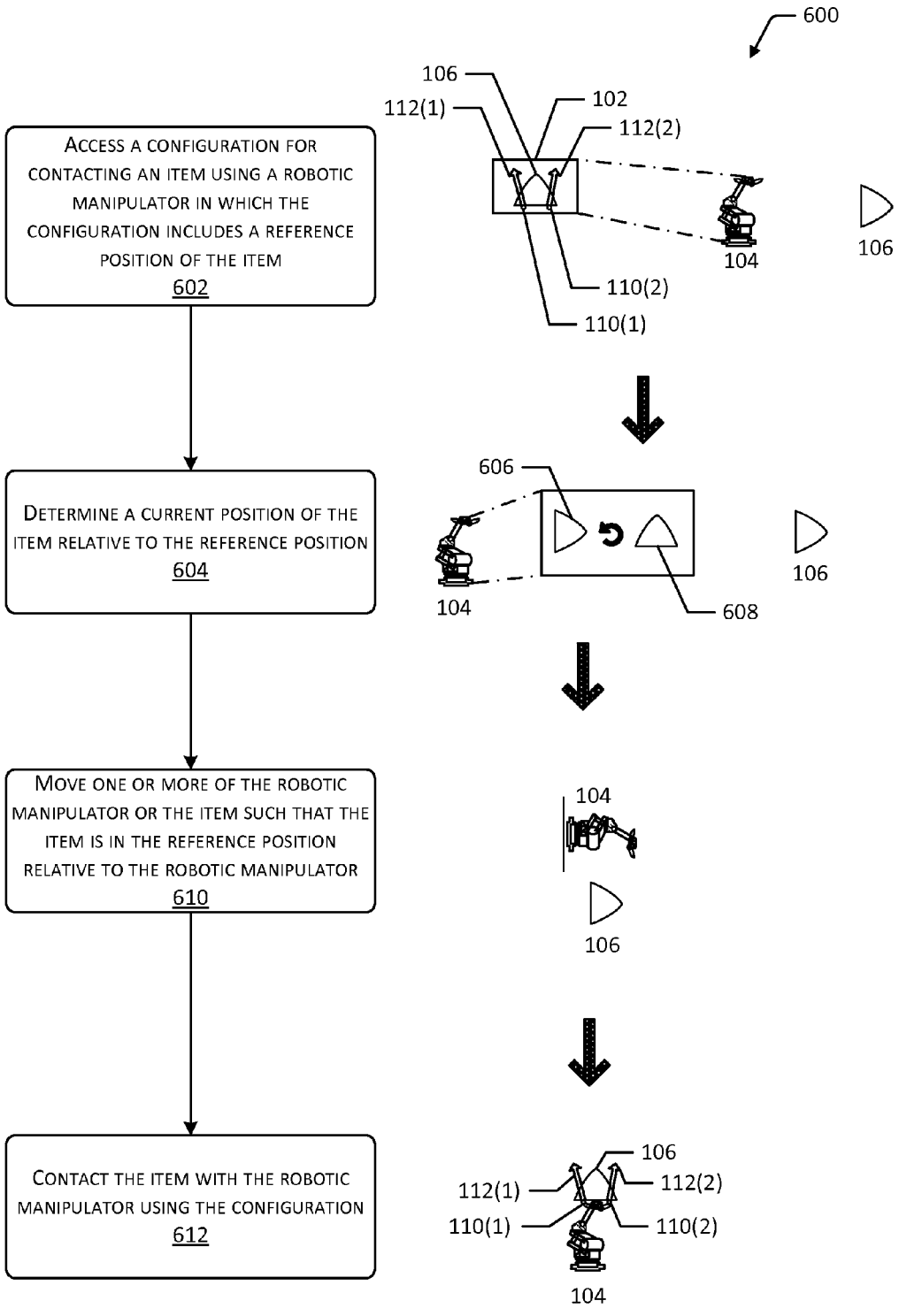

ACCESS A CONFIGURATION FOR CONTACTING AN ITEM USING A ROBOTIC MANIPULATOR IN WHICH THE CONFIGURATION INCLUDES A REFERENCE POSITION OF THE ITEM
602
DETERMINE A CURRENT POSITION OF THE ITEM RELATIVE TO THE REFERENCE POSITION
604
MOVE ONE OR MORE OF THE ROBOTIC MANIPULATOR OR THE ITEM SUCH THAT THE ITEM IS IN THE REFERENCE POSITION RELATIVE TO THE ROBOTIC MANIPULATOR
610
CONTACT THE ITEM WITH THE ROBOTIC MANIPULATOR USING THE CONFIGURATION
612
600
106
112(1)
102
112(2)
104
106
110(2)
110(1)
606
608
104
106
104
106
106
112(1)
112(2)
110(1)
110(2)
104

FIG. 6

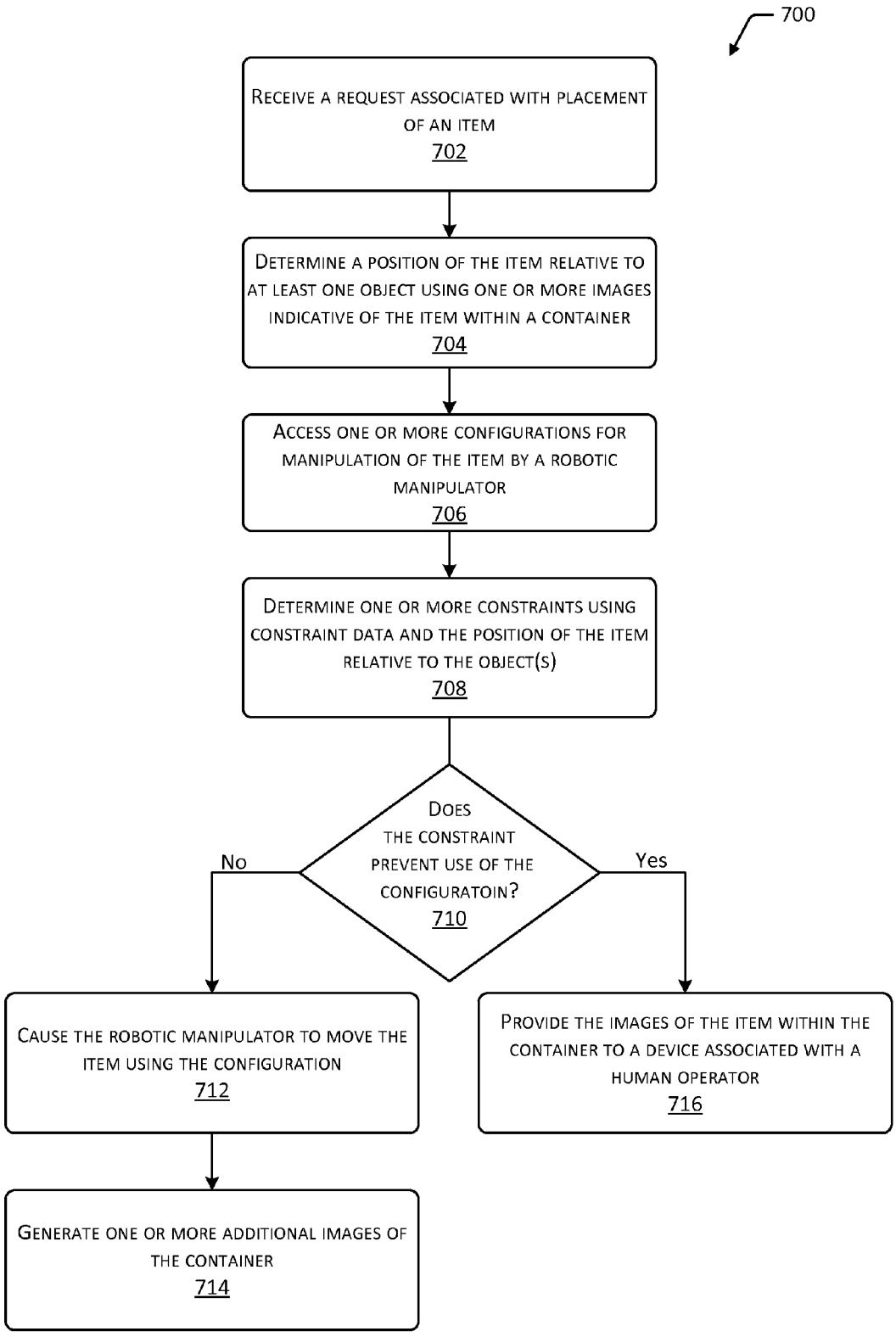

700
Receive a request associated with placement of an item
702
Determine a position of the item relative to at least one object using one or more images indicative of the item within a container
704
Access one or more configurations for manipulation of the item by a robotic manipulator
706
Determine one or more constraints using constraint data and the position of the item relative to the object(s)
708
Does the constraint prevent use of the configuratoin?
710
No
Yes
Cause the robotic manipulator to move the item using the configuration
712
Generate one or more additional images of the container
714
Provide the images of the item within the container to a device associated with a human operator
716

FIG. 7

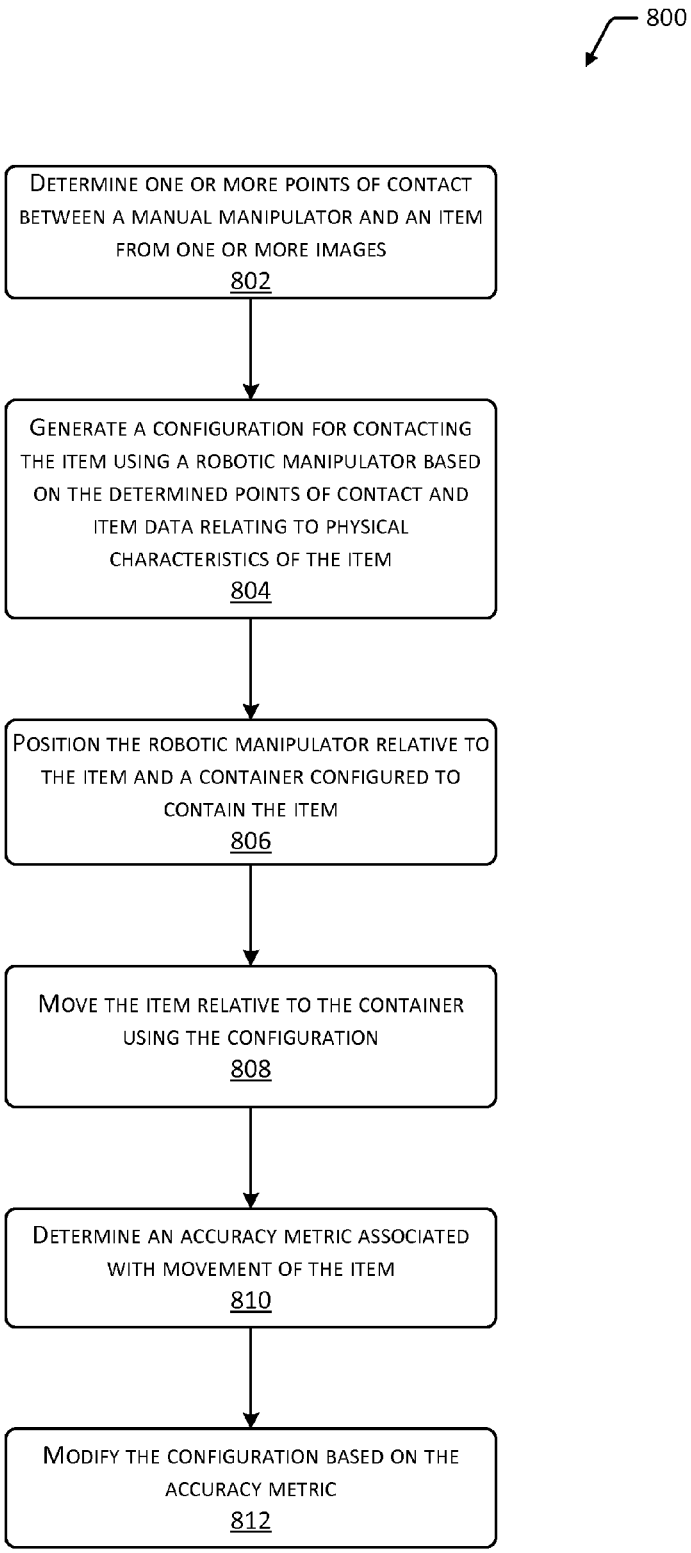

800
DETERMINE ONE OR MORE POINTS OF CONTACT BETWEEN A MANUAL MANIPULATOR AND AN ITEM FROM ONE OR MORE IMAGES
802
GENERATE A CONFIGURATION FOR CONTACTING THE ITEM USING A ROBOTIC MANIPULATOR BASED ON THE DETERMINED POINTS OF CONTACT AND ITEM DATA RELATING TO PHYSICAL CHARACTERISTICS OF THE ITEM
804
POSITION THE ROBOTIC MANIPULATOR RELATIVE TO THE ITEM AND A CONTAINER CONFIGURED TO CONTAIN THE ITEM
806
MOVE THE ITEM RELATIVE TO THE CONTAINER USING THE CONFIGURATION
808
DETERMINE AN ACCURACY METRIC ASSOCIATED WITH MOVEMENT OF THE ITEM
810
MODIFY THE CONFIGURATION BASED ON THE ACCURACY METRIC
812

FIG. 8

SYSTEM FOR AUTOMATING MANIPULATION OF ITEMS

BACKGROUND

Many storage facilities use computer-assisted processes to catalog the specific locations of stored items within the facility. In some facilities, storage containers, such as shelves, bins, and so forth, may be mechanically transported to various locations within the facility, including locations accessible by human operators. Human operators, however, are responsible for locating specific items within a container for retrieval, and for placing additional items into a container for stowage.

BRIEF DESCRIPTION OF FIGURES

The detailed description is set forth below with reference to the accompanying figures. In the figures, the left-most digit(s) of a reference number identifies the figure in which the reference number first appears. The use of the same reference numbers in different figures indicates similar or identical items or features.

FIG. **1** depicts a system for determining one or more configurations by which one or more robotic manipulators may interact with one or more items.

FIG. **2** is a block diagram illustrating examples of images, sensor data, constraint data, and item data.

FIG. **3** is a block diagram illustrating a computing device within the scope of the present disclosure.

FIG. **4** is a scenario for generating one or more configurations for a robotic manipulator to contact an item using sensor data obtained from a human operator.

FIG. **5** is a scenario for determining one or more constraints that may prevent one or more robotic manipulators from accessing an item.

FIG. **6** is a scenario for using a configuration for a robotic manipulator to contact an item when the configuration is based on a reference position of the item.

FIG. **7** is a flow diagram illustrating a process for determining whether a configuration for a robotic manipulator may be used to move an item based on the position of the item within a container relative to other objects.

FIG. **8** is a flow diagram illustrating a process for generating a configuration for contacting the item, determining an accuracy metric associated with the configuration, and modifying the configuration based on the accuracy metric.

While implementations are described herein by way of example, those skilled in the art will recognize that the implementations are not limited to the examples or figures described. It should be understood that the figures and detailed description thereto are not intended to limit implementations to the particular form disclosed but, on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope as defined by the appended claims. The headings used herein are for organizational purposes only and are not meant to be used to limit the scope of the description or the claims. As used throughout this application, the word "may" is used in a permissive sense (i.e., meaning having the potential to) rather than the mandatory sense (i.e., meaning must). Similarly, the words "include," "including," and "includes" mean including, but not limited to.

DETAILED DESCRIPTION

Items retained in inventory associated with a merchant or vendor are typically stowed at a storage facility, such as a warehouse. When additional items for inventory are received, they are stowed in the facility, and the location of the one or more items within the facility may be recorded to enable subsequent retrieval. When an item is purchased or other events, such as movement of items between locations within a facility, make it necessary to retrieve the item, the recorded location of the item may be accessed, and the item may be removed from the facility or moved to another location within the facility. Changes in the locations of the items, including removal of the items, may similarly be recorded. Computer-based systems may be used to facilitate maintenance of an accurate log of the location of each item within one or more facilities, providing increased efficiency and fewer errors over manual means, which may be subject to inaccurate entries of items or locations. In some facilities, storage containers, such as shelves, bins, crates, totes, and so forth, may be mechanically moved between locations within a facility, reducing the need for human operators to travel to the location of a container or move containers through manual means. Due to unique physical characteristics of each item, and the unique arrangement of items within each container, the acts of placing items into containers and removing items from containers may be performed by human operators. For example, human operators may grip, lift, move, or otherwise manipulate items by hand or using another manual manipulator. Manual manipulators may include human hands; suction-based, vacuum-based, or ferromagnetic hand tools; lifting devices such as forklifts; and so forth. Many stowage and retrieval processes performed by human operators, such as locating a specific item within a container containing numerous other items, are prone to inefficiency and error. For example, human operators may require significant time to locate a single item within a container, may retrieve an improper item, may stow an item in an improper location, may fail to properly record stowage or retrieval of an item, and so forth.

Described herein are techniques for automating one or more stowage and retrieval processes by enabling such processes to be performed using a robotic manipulator, such as a robotic hand or a similar robotic gripping or support device. Robotic gripping devices may include vacuum lifters, suction-based grippers, ferromagnetic-based grippers, and so forth. Images depicting one or more human operators interacting with an item, such as images showing the position of an operator's hand(s) when gripping or lifting an item, may be accessed from a data store. For example, images of a human operator interacting with an item may be obtained using one or more cameras and stored for subsequent use in association with a robotic manipulator to generate a model from which configurations for interaction between the robotic manipulator and the item may be determined. In some implementations, a human operator may be instrumented with position sensors for determining the position of the operator's hands or other body portions, force sensors for determining the force applied to an item by the operator's hands or other body portions, or both position sensors and force sensors. For example, a human operator may wear gloves or other articles having sensors associated therewith. In other implementations, an item with which a human operator interacts may be instrumented with one or more of position sensors or force sensors. From the images and sensor data, one or more points of contact between the human operator and the item may be determined. One or more force vectors associated with at least a portion of the points of contact may also be determined from the images and sensor data.

In some implementations, item data relating to one or more physical characteristics of an item, such as the item's weight,

dimensions, weight distribution (e.g., center of mass), material characteristics (e.g., durability and compressibility), and so forth, may be accessed. In some implementations, constraint data may be accessed from a data store. Constraint data may include limitations regarding one or more of the following: the movement of a robotic manipulator; the types of items or containers with which the robotic manipulator may interact; the locations at which the robotic manipulator may be operated; physics-based constraints, such as certain forces or points of contact that may not successfully grip or support an item independent of the physical limitations of the robotic manipulator or the item; and so forth.

The information determined from the images and sensors, the item data, and the constraint data may be used to generate one or more possible configurations of the robotic manipulator with respect to an item. Each configuration may include one or more points of contact between the robotic manipulator and the item as well as one or more force vectors associated with at least a portion of the points of contact. For example, based on characteristics of an item determined from the images and the item data, and based on constraint data relating to the item and the robotic manipulator, a model may be generated. The model may include one or more suitable points of contact at which the item may be contacted by a robotic manipulator. The points of contact may be determined, for example, based on the weight distribution and material characteristics of the item. The suitable points of contact may be constrained based on the configuration and capabilities of the robotic manipulator. Each point of contact may include a maximum force vector that may be applied thereto, also determined from the item data or constraint data. When multiple possible configurations are determined, the configuration that is most suitable for accessing the item at its current location may be determined and executed. For example, different configurations may be used depending on the orientation of an item.

A configuration may be executed when a request associated with placement of an item is received. For example, a request may include an instruction to place an item into a container or to retrieve a stored item. Location data corresponding to the item may be accessed from a data store. The location data may include one or more of the current location of a stowed item, the current location of an item to be stowed, or the destination stowage location of an item to be stowed. One or more of the robotic manipulator, the item, or a container containing the item may be moved into a position such that the robotic manipulator may contact and move the item. The robotic manipulator may contact one or more portions of the item that correspond to the points of contact in the determined configuration. The robotic manipulator may also apply one or more forces to the item that correspond to the force vectors in the determined configuration, to move the item into or from a container or other location.

In some implementations, one or more images may include a current location of the item relative to one or more additional objects, such as an image depicting the item within a container alongside other objects. Other objects may include additional items, walls or other portions of the container, debris, packaging materials, and so forth. From the one or more images, one or more constraints relating to the robotic manipulator may be determined. For example, passage of the robotic manipulator between the item and one or more additional objects or manipulation of the item relative to one or more additional objects may be restricted or impossible. Continuing the example, the arrangement of the objects, the sides of the container, and so forth may inhibit movement of the robotic manipulator. Configurations by which the robotic manipulator may interact with the item may be modified or restricted based on the one or more constraints determined from the one or more images. If no configuration for interaction with the item may be determined based on the one or more images, an indication of the one or more constraints may be provided to a computing device associated with a human operator to enable a human operator to complete tasks not suitable for completion using the robotic manipulator.

In some implementations, an indication of one or more constraints may be provided to the device associated with a human operator based on the item data or the constraint data. For example, the dimensions, weight, shape, material characteristics, and so forth, of an item may indicate that an item cannot be safely or effectively handled using a robotic manipulator. An indication provided to the device associated with the human operator may describe the characteristics of the item that cause the item to be unsuitable for manipulation by the robotic manipulator. In another example, the shape or current location of an item may prevent access to the item by the robotic manipulator due to limitations in the range of movement of the robotic manipulator or the dimensions thereof. In some implementations, items or containers suitable for access by a robotic manipulator may be stowed at a location within a facility that is readily accessible to the robotic manipulator. Items or containers unsuitable for access by a robotic manipulator may be stowed at other locations readily accessible to human operators.

In some implementations, one or more determined configurations of a robotic manipulator may be modified using an accuracy metric, which may include a determination of the effectiveness of a configuration. The effectiveness of a configuration may be measured using a physical test. For example, the robotic manipulator may be positioned relative to an item and a container configured to contain the item. The robotic manipulator may then be used to contact one or more portions of the item corresponding to the points of contact of the determined configuration. The robotic manipulator may also apply forces to the points of contact that correspond to the force vectors of the determined configuration to move the item relative to the container. An accuracy metric associated with movement of the item may be determined, and the configuration may be modified based, at least in part, on the accuracy metric. For example, if attempted movement of an item by the robotic manipulator damages or drops the item, the location of one or more points of contact between the robotic manipulator and the item or one or more forces applied by the robotic manipulator may be modified based on this determination. Continuing the example, if an item is dropped during transport by the robotic manipulator, the configuration may be modified to apply a greater force to one or more portions of the item such that the robotic manipulator grips the item more tightly. If an item rotates or moves significantly during transport by the robotic manipulator, the configuration may be modified to increase the surface area of one or more points of contact or more widely space the points of contact apart to provide the item with increased stability. In some implementations, one or more of the item or the robotic manipulator may be provided with a support that prevents falling of the item in the event that the configuration applied by the robotic manipulator fails to securely grip or stabilize the item. In other implementations an accuracy metric may be determined by analyzing an item within a container, such as through use of one or more cameras. The position of the item, within three dimensions, may be compared to images depicting the interactions between human operators and the item to determine whether a particular configuration may be more accurate than other configurations based on the current posi-

tion of the item and the depicted images that most closely match the position of the item.

In some implementations, configurations may be determined based on a reference position (e.g., orientation) of an item. To manipulate an item, the robotic manipulator may be positioned relative to the item, or the item may be positioned relative to the robotic manipulator. Movement of the item, the robotic manipulator, or both the item and robotic manipulator may result in the item being oriented in the reference position relative to the robotic manipulator. In other implementations, the item may be moved, using the robotic manipulator or other means, such as other automated devices or manually by a human operator, to position the item in the reference position relative to the robotic manipulator.

Techniques described herein may enable automation of stowage and retrieval operations in a facility while identifying operations better suited for human operators. Techniques described herein may be implemented using data obtained from normal operations, such as images depicting human operators interacting with items, and sets of known constraints. Automation of stowage and retrieval operations may increase efficiency and reduce errors by reducing the time expended locating items and reducing the possibility of improperly placing items or retrieving improper items.

FIG. **1** depicts a system **100** for determining one or more configurations **102** that enable one or more robotic manipulators **104** to interact with an item **106**. For example, a human operator **108** may grip, lift, move, or otherwise manipulate an item **106** using hands, other portions of the body, or other manual manipulators. Other manual manipulators may include vacuum-based, suction-based, friction-based, adhesive-based, or ferromagnetic-based hand tools, lifting devices such as forklifts, and so forth. The manner in which the human operator **108** interacts with the item **106** may include one or more points of contact **110** between the human operator **108** and the item **106** or between a manual manipulator and the item **106**. The human operator **108** may apply one or more forces to one or more of the points of contact **110**, each force having a magnitude and a direction, thereby defining one or more force vectors **112**.

Implementations described herein may enable one or more robotic manipulators **104** to interact with an item **106** by determining configurations **102** for the robotic manipulator (s) **104** that include points of contact **110** and force vectors **112** based on the points of contact **110** and force vectors **112** used by a human operator **108**. In some implementations, the points of contact **110** and force vectors **112** may directly correspond to those used by the human operator **108**. However, in other implementations, the configuration(s) **102** may include a larger or smaller number of points of contact **110** or different force vectors **112** than those used by the human operator **108** due to other constraints. For example, the manner in which a human operator **108** contacts an item **106** may be used to generate a model associated with the item **106**. Constraints associated with the robotic manipulator **104** or the item **106** may prevent use of the same points of contact **110** and force vectors **112** applied by the human operator **108**. The model of the item **106** and the known constraints may be used to determine a configuration **102** suitable for use with the robotic manipulator **104**. Example constraints may include limitations on a range of movement of the robotic manipulator(s) **104**, the type of gripping or support elements used by a robotic manipulator **104**, characteristics of the item **106**, characteristics of a location of the item **106**, and so forth. For example, the center of mass of an item **106** and the material characteristics thereof may be determined from a human operator **108** interacting with the item **106**. Rather than duplicating the points of contact **110** and force vectors **112** applied by the human operator **108**, a configuration **102** generated for use with the robotic manipulator **104** may include alternate points of contact **110** and force vectors **112** based on the item **106** characteristics and the constraints associated with the robotic manipulator **104**.

Robotic manipulators **104** may include any manner of robotic devices configured to contact and move one or more items **106**. In some implementations, the robotic manipulator (s) **104** may include a robotic arm and hand that simulates a human hand, having five fingers, 27-degrees of freedom of movement, and so forth. In other implementations, a robotic arm and hand having fewer than five digits may be used. In still other implementations, robotic manipulators **104** may include other types of gripping or lifting mechanisms, such as a platform similar to a forklift or spatula, suction-based grippers, vacuum-based grippers, ferromagnetic-based grippers, adhesive-based grippers, friction-based grippers, grippers configured to at least partially penetrate an item **106**, and so forth. The configurations **102** determined for interaction between a robotic manipulator **104** and an item **106** may be based, at least in part, on the specific characteristics of the robotic manipulator **104** used. While FIG. **1** depicts a single robotic manipulator **104**, in some implementations, multiple robotic manipulators **104** may be used. For example, two robotic manipulators **104** may be used to interact with an item **106** in a manner simulating two human hands. Continuing the example, multiple robotic manipulators **104** may be used to interact with an item **106** in a manner simulating more than one human operator **108**.

The interactions of a human operator **108** with the item **106** may be recorded using one or more sensors **114**. One or more cameras **116** or other types of image sensors may be used to generate one or more images **118** of the human operator **108** interacting with the item **106**. In some implementations, multiple cameras **116** may be used to generate images **118** of one or more of the human operator **108** or the item **106** from multiple viewpoints. For example, in FIG. **1**, a first camera **116**(**1**) is depicted at a first position relative to the human operator **108** and the item **106**, and a second camera **116**(**2**) is depicted at a second position relative to the human operator **108** and the item **106**. Any number or types of cameras **116** may be used. One or more cameras **116** may include depth cameras (e.g., Red-Green-Blue plus Depth (RGB-D) cameras) or other types of depth sensors such as time-of-flight (ToF), flash lidar, or range cameras, which may be used to determine a distance between the camera **116** and the human operator **108** or the item **106**.

The camera(s) **116** or other image sensors may be configured to detect light in one or more wavelengths including, but not limited to, terahertz, infrared, visible, ultraviolet, and so forth. The camera(s) **116** or other image sensors may include charge coupled devices (CCD), complementary metal oxide semiconductor (CMOS) devices, microbolometers, and so forth. In some implementations, the camera(s) **116** or other image sensors may include integrated or discrete light sensors configured to provide information associated with ambient lighting conditions such as a level of illumination.

In some implementations, one or more of the human operator **108** or the item **106** may have one or more other types of sensors **114** associated therewith. For example, one or more sensors **114** may be positioned on the body of the human operator **108**, such as integrated within a glove or other article of clothing or jewelry. In other implementations, one or more sensors **114** may be positioned on the item **106**. In still other implementations, sensors **114** may be associated with a manual manipulator used by a human operator **108** to interact

with the item **106**. The sensors **114** may include one or more force sensors, which may determine sensor data **120**, indicative of a force applied by the human operator **108** to the item **106** at one or more points of contact **110** between the human operator **108** or manual manipulator and the item **106**. Force sensors may include one or more load cells, strain gauges, transducers, force sensitive resistors, pressure sensors, touch sensors, and so forth.

In some implementations, the sensors **114** may include position sensors, which may determine sensor data **120** indicative of the position or pose of one or more parts of the body of the human operator **108**, another manual manipulator, or item **106**. Position sensors may include proximity sensors, touch sensors, radio frequency identification (RFID) or near field communication (NFC) sensors, orientation or motion sensors, three-dimensional (3D) sensors, location sensors, and so forth. For example, a proximity sensor may use optical, electrical, ultrasonic, electromagnetic, or other techniques to determine a presence of an object. Continuing the example, an optical proximity sensor may use ToF, structured light, interferometry, or other techniques to generate distance data. Touch sensors may use resistive, capacitive, surface capacitance, projected capacitance, mutual capacitance, optical, Interpolating Force-Sensitive Resistance (IFSR), or other mechanisms to determine the position of a touch or near-touch of an object. For example, IFSR material may be configured to change electrical resistance responsive to an applied force. The location within the material of the change in electrical resistance may indicate the position of a touch. RFID sensors may include RFID readers configure to detect RFID tags, RFID receivers configured to detect RFID readers, and so forth. RFID tags may be configured to emit a radio frequency signal, such as upon activation by an external signal. Such external signals may include, for example, a radio frequency signal or a magnetic field. Orientation or motion sensors may include a gyroscope, a magnetometer, an accelerometer, and so forth. For example, a magnetometer may determine an orientation of a sensor **114** associated with an object by measuring ambient magnetic fields, such as the terrestrial magnetic field. 3D sensors may acquire spatial or 3D data, such as distance, 3D coordinates, point cloud, and so forth, about objects within a sensor's **114** field-of-view. For example, 3D sensors may include range cameras, lidar systems, sonar systems, radar systems, coded aperture systems, structured light systems, stereo vision systems, optical interferometry systems, and so forth. Location sensors may include radio navigation-based systems such as terrestrial or satellite-based navigational systems. The satellite-based navigational systems may include a Global Positioning System (GPS) receiver, a global navigation satellite system (GLONASS) receiver, a Galileo receiver, a BeiDou Navigation Satellite System (BDS) receiver, an Indian Regional Navigational Satellite System, and so forth.

FIG. **1** depicts the cameras **116** and sensors **114** providing images **118** and sensor data **120** to one or more servers **122**. The server(s) **122** may store one or more modules and one or more types of data for determining configurations **102** by which the robotic manipulator(s) **104** may interact with the one or more items **106**. While FIG. **1** depicts the server(s) **122** in communication with the cameras **116**, sensors **114**, and robotic manipulator(s) **104**, in some implementations, the cameras **116** and sensors **114** may communicate directly with the robotic manipulator(s) **104**. In other implementations, one or more other computing devices may be provided in communication with the robotic manipulator(s) **104**, the cameras **116**, and the sensors **114**. Computing devices may include mobile devices, smartphones, set-top boxes, tablet computers, personal computers, wearable computers, or other types of computing devices. The cameras **116**, sensors **114**, robotic manipulator(s) **104**, server(s) **122**, and other computing devices may communicate using one or more networks (not shown), which may include, without limitation, a personal area network (PAN), local area network (LAN), wide area network (WAN), and so forth. Networks may communicate using Ethernet, Wi-Fi®, Bluetooth®, ZigBee®, 3G, 4G, LTE, Z-Wave, or other technologies.

An image processing module **124** stored on the server **122** may be used to process one or more images **118** received from the cameras **116** or other image sensors. For example, images **118** depicting a human operator **108** gripping or lifting an item **106** may be used to determine points of contact **110** between the body of the human operator **108** and the item **106**. The direction of one or more force vectors **112** applied by the human operator **108** may be determined from the image(s) **118**. For example, the pose of the body of the human operator **108** may indicate the approximate direction in which one or more forces were applied to the item **106**. In some implementations, the approximate magnitude of one or more of the force vectors **112** may be determined from the image(s) **118**. For example, the pose of the body of the human operator **108** or visible deformation of the item **106** may be used to determine the magnitude of a force applied to the item **106**, such as by enabling the approximate weight of the item to be determined. Continuing the example, the pose of the body of the human operator **108** may be used to determine if an item **106** is "heavy" or "not heavy." Operations relating to items **106** determined to be heavy may be provided to human operators **108** or to robotic manipulators **104** adapted for use with heavy items **106**. In other implementations, the position, movement, or deformation of the item **106** relative to the human operator **108** may be used to determine material characteristics of the item **106**. The image(s) **118** may also be used to determine the shape and the approximate dimensions of the item **106**. In one implementation, the image processing may be performed at least in part by using one or more tools available in the OpenCV library as developed by Intel Corporation of Santa Clara, Calif., USA; Willow Garage of Menlo Park, Calif., USA; and Itseez of Nizhny Novgorod, Russia, with information available at www.opencv.org.

A sensor processing module **126** may be stored on the server **122** and used to process sensor data **120** received from one or more sensors **114**. For example, the sensor processing module **126** may determine one or more of the magnitude or direction of the force vectors **112** applied by the human operator **108** to the item **106** from sensor data **120** provided by force sensors. Continuing the example, the sensor processing module **126** may determine one or more points of contact **110** with the item **106** from sensor data **120** provided by one or more positions sensors, location sensors, touch sensors, proximity sensors, and so forth.

A constraint module **128** may be stored on the server **122** and may access constraint data **130** relating to constraints of the robotic manipulator(s) **104**, the item **106**, a location at which the item **106** or the robotic manipulator(s) **104** are positioned, or one or more physics-based constraints. The constraint module **128** may be used to determine constraints that limit configurations **102** able to be used by the robotic manipulator(s) **104** with the item **106**. For example, the specific type of gripping mechanism used by the robotic manipulator **104** may prevent the robotic manipulator **104** from simulating each point of contact **110** provided to the item **106** by a human operator **108**. Continuing the example, a robotic manipulator **104** lacking a gripping appendage with five fingers may be unable to duplicate the grip provided by a human

hand. In another example, the item **106** may be positioned in a location having close tolerances, such as a full or mostly-full container, that are smaller than the dimensions of at least a portion of the robotic manipulator **104**, such that the robotic manipulator **104** may not be able to access the item **106**. Similarly, depending on the nature of the facility in which the item **106** is located, it may not be possible for the robotic manipulator **104** or the item **106** to be moved within proximity of one another to enable the robotic manipulator **104** to interact with the item **106**. In some implementations, the constraint module **128** may determine one or more constraints based on one or more characteristics or the nature of the item **106**. For example, an item **106** that is fragile, compressible or bendable, or irregularly shaped may be unsuitable for handling by a robotic manipulator **104** or may require a unique configuration **102** based on a model of the item **106** determined from the images **118** and the characteristics of the item **106**. The shape or durability of the item **106** may be determined using images **118**, sensor data **120**, stored data regarding the item **106**, and so forth.

The constraint data **130** may include one or more physics-based constraints. In some implementations, the constraint module **128** may determine that one or more configurations **102** between the robotic manipulator(s) **104** and the item **106** that may be possible to implement may likely result in dropping of the item **106**, gripping of the item **106** in excess of the tolerance thereof, or damage to the item **106** or robotic manipulator(s) **104**. For example, a configuration **102** that includes a single point of contact **110** between a robotic manipulator **104** and an item **106** may be possible to implement, but it may be unlikely that such a configuration **102** may securely retain an item **106** in association with the robotic manipulator **104** for a length of time necessary to move the item **106** to a different location.

A configuration generating module **132** may also be stored on the server **122** and used to determine one or more configurations **102** by which the robotic manipulator(s) **104** may interact with items **106**. The configuration generating module **132** may process the data generated by the image processing module **124** from the one or more images **118**, the sensor data **120** from the sensor processing module **126**, one or more constraints determined by the constraint module **128** using the constraint data **130**, and item data **134** relating to one or more physical characteristics of the item **106** to determine one or more configurations **102**. Physical characteristics of the item **106** may include the weight, dimensions, shape, a distribution of weight, material characteristics (e.g., durability, fragility, etc.), and so forth, of the item **106**.

In some implementations, the image processing module **124** may determine one or more points of contact **110** between a human operator **108** and an item **106** using images **118** acquired by the cameras **116**. The sensor processing module **126** may determine one or more force vectors **112** applied to the item **106** by the human operator **108**. Using these determinations and the item data **134**, the configuration generating module **132** may determine one or more combinations of points of contact **110** and force vectors **112** that may effectively grip, lift, or otherwise manipulate the item **106**. However, characteristics of the robotic manipulator(s) **104**, such as range of motion, dimensions, the number and type of appendages used to manipulate items **106**, and so forth, may limit the ability of the robotic manipulator(s) **104** to duplicate all points of contact **110** and force vectors **112** determined by the image processing module **124** and the sensor processing module **126**. Responsive to constraints determined by the constraint module **128**, the points of contact **110** and force vectors **112** initially determined by the configuration generation module **132** may be modified. For example, a robotic manipulator **104** that lacks a five-fingered appendage may apply fewer points of contact **110** to the same portion of an item **106** than the points of contact **110** applied by a human operator **108**. One or more points of contact **110** applied by the robotic manipulator **104** may include an increased surface area or may be more widely spaced apart to provide similar stability to the item **106** even though the grip of the human operator **108** is not identically duplicated by the robotic manipulator **104**. In some implementations, one or more points of contact **110** or force vectors **112** may be discarded as unsuitable or impossible based on constraints determined by the constraint module **128**. In other implementations, the points of contact **110** and force vectors **112** used by the robotic manipulator **104** may differ from those used by a human operator **108**. For example, images **118** depicting interactions between human operators **108** and an item **106**, item data **134** relating to the item **106**, and constraint data **130** relating to physics-based constraints may be used to generate a model of interactions between the item **106** and the robotic manipulator **104**. Using the model and the constraint data **130**, a set of points of contact **110** and force vectors **112** that may be used by the robotic manipulator **104**, may be determined. For example, item data **134** and images **118** depicting the interaction of human operators **108** with an item **106** may be used to determine a center of mass associated with the item **106**. Points of contact **110** between the human operators **108** and the item **106** may be determined from the images **118**. In some implementations, constraints relating to the robotic manipulator **104** or to the item **106**, or physics-based constraints, may prevent use of the robotic manipulator **104** to simulate the same points of contact **110**. A configuration **102** including other points of contact **110** and associated force vectors **112**, suitable for use by the robotic manipulator **104**, may be determined from the model. The determined configuration **102** may correspond to the constraints of the robotic manipulator **104** and the item **106**.

The configuration generation module **132** may produce one or more configurations **102** based on the image(s) **118**, sensor data **120**, constraint data **130**, and item data **134**. The configuration(s) **102** may be provided to the robotic manipulator(s) **104** for interacting with items **106**. When multiple possible configurations **102** for interacting with an item **106** are determined, the configuration generation module **132** or the robotic manipulator(s) **104** may determine which of the multiple configurations **102** will result in the most stable manipulation of the item **106** without causing damage thereto. For example, a robotic manipulator **104** or a server **122** in communication therewith may determine a current location of the item **106**. In some implementations, a first configuration **102** may be determined to be more suitable for use at a first location, while a second configuration **102** may be more suitable for use at a second location. In other implementations, a robotic manipulator **104** or a server **122** in communication therewith may determine an orientation of the item **106**. A first configuration **102** may be more suitable for contacting the item **106** in a first orientation, while a second configuration **102** may be more suitable for contacting the item **106** in a second orientation.

When a request from a computing device to retrieve or stow an item **106** is received by the server(s) **122**, the robotic manipulator(s) **104**, or other computing device(s) in communication therewith, location data **136** in the server(s) **122** relating to the location of the item **106** may be accessed. In some implementations, one or more robotic manipulators **104** may be moved into association with the item **106** or a container containing the item **106** to enable the robotic manipu-

lator(s) **104** to interact with the item **106**. In other implementations, the item **106** or the container containing the item **106** may be moved to a distance from the robotic manipulator(s) **104** suitable for interaction therewith. When the robotic manipulator(s) **104** and the item **106** are positioned relative to one another, the robotic manipulator(s) **104** may be used to contact the item at the point(s) of contact **110** determined by the configuration **102** and to apply forces corresponding to the force vectors **112** of the configuration **102**. In some implementations, the robotic manipulator(s) **104** may include one or more cameras **116** or similar sensors **114** usable to determine the location of the item **106** within a container or similar location. While FIG. **1** depicts the item **106** as an object having the shape of a rectangular prism, which may represent a box, crate, or similar packaging materials, configurations **102** may be determined for any manner of item **106**, having any shape, dimensions, weight, weight distribution, and so forth.

In some implementations, the location data **136** may be used by the constraint module **128** to render one or more configurations **102** unusable. For example, the location data **136** may indicate that an item **106** is positioned at a location inaccessible to the robotic manipulator(s) **104**. The location data **136** may also indicate the item **106** is positioned among other objects or containers in a manner that provides insufficient clearance for passage of the robotic manipulator(s) **104**. In circumstances where constraints prevent use of the robotic manipulator(s) **104** to retrieve or store an item **106**, an indication may be provided to one or more devices associated with human operators **108** to facilitate performance of the operation by a human operator **108**.

FIG. **2** is a block diagram **200** illustrating example implementations of images **118**, sensor data **120**, constraint data **130**, and item data **134** that may be used with the system **100** shown in FIG. **1**.

One or more images **118** may be acquired using cameras **116** or other types of sensors **114**. The image processing module **124** may process received images **118** to determine points of contact **110** and force vector(s) **112** applied by a human operator **108** to an item **106**. Images **118** may also be processed to determine characteristics of the item **106** and one or more constraints that may limit the configurations **102** used by a robotic manipulator **104** to manipulate an item **106**.

A first image **118**(**1**) is shown depicting a human operator **108** gripping and lifting an item **106**. A first point of contact **110**(**1**) and a second point of contact **110**(**2**) between the hands of the human operator **108** and the item **106** are shown in the image **118**(**1**). Processing of the first image **118**(**1**) by the image processing module **124** may determine one or more of the following: the depicted points of contact **110**, other points of contact **110** not visible in the image **118**(**1**) but able to be determined from other depicted items such as the pose of the human operator **108**, one or more forces applied by the human operator **108** to the item **106**, or one or more characteristics of the item **106**. For example, the pose of the body of the human operator **108** may be used to determine a possible weight range or an approximate weight of the item **106** (e.g., "heavy," "not heavy") and forces applied by the human operator **108** thereto. The relative sizes of the item **106** and the human operator **108** may be used to determine approximate dimensions of the item **106** or of the human operator **108**. One or more other objects visible in the first image **118**(**1**) may enable determination of the location of the human operator **108** and item **106** at the time the image **118**(**1**) was generated. In some implementations, the constraint module **128** may determine one or more constraints based on the depicted human operator **108** or item **106**. For example, certain points of contact **110** or force vectors **112** determined from the first image **118**(**1**) may be unsuitable for performance by a robotic manipulator **104**.

A second image **118**(**2**) is shown depicting the item **106** in a form in which it may be stowed. For example, the depicted item **106** may be packaged in a box, crate, or similar container. Because most items **106** are typically stowed in a packaged form, an image **118** depicting an item **106** in the form in which it was stowed may facilitate locating the item **106** within a container or other location, such as when using cameras other sensors associated with a robotic manipulator **104**. An image **118** depicting the item **106** in the form in which it was stowed may also assist a human operator **108** in locating the item **106** when a robotic manipulator **104** is unable to access the item **106**. Additionally, the image processing module **124** may determine one or more characteristics of the item **106** from the second image **118**(**2**), including the shape, dimensions, weight, weight distribution, or materials of an item **106**. In some implementations, the constraint module **128** may determine one or more constraints based on one or more characteristics of the item **106**. For example, a robotic manipulator **104** may be unsuitable for handling a fragile or irregularly-shaped item **106**. The shape or fragility of an item **106** may be determined from item data **134** associated with the item **106**, sensor data **120** or images **118** associated with the item **106**, and so forth.

A third image **118**(**3**) is shown depicting the item **106** stowed within a container **202**. The container **202** is also shown containing a first object **204**(**1**), a second object **204**(**2**), and a third object **204**(**3**). Objects **204** within the container **202** may include other items **106**, debris, protrusions or other structural portions of the container **202**, and so forth. The image processing module **124** may use the third image **118**(**3**) to determine the location of the item **106** relative to the objects **204** and relative to the walls, floor, and ceiling of the container **202**. In some implementations, a depth or range camera **116** may be used to determine a depth of the container **202** at one or more points by determining the distance of the item **106**, one or more objects **204**, or a surface of the container **202** from the camera **116**. For example, the third image **118**(**3**) is shown including a determined depth D**1** at a first point in the container **202** aligned with the item **106**. The depth D**1** may thereby indicate a distance between the camera **116** and the item **106**. A second determined depth D**2** at a second point in the container **202** is also shown. The second depth D**2** is aligned with the far surface of the container **202** and may be used to determine the total depth of the container **202**. In some implementations, the depth D**1** associated with the item **106** and the depth D**2** associated with the container **202** may be used to determine a height of the item **106**. An image **118**(**3**) depicting the container **202** containing the item **106**, illustrating where the item **106** is stored relative to other objects **204** and the surfaces of the container **202** may facilitate locating of the item **106** by a robotic manipulator **104**. An image **118** depicting the container **202** and the contents thereof in the form in which it was stowed may also assist a human operator **108** in locating the item **106** when a robotic manipulator **104** is unable to access the item **106**. In some implementations, the constraint module **128** may determine one or more constraints based on the location, orientation, or placement of the item **106** within the container **202**. For example, the position of other objects **204** or the surfaces of the container **202** may prevent passage of a portion of the robotic manipulator **104** necessary to engage the item **106**.

Sensor data **120** may include data received from one or more types of sensors **114**. Any portion of a facility, human operator **108**, item **106**, manual manipulator used by a human

operator **108**, container **202**, or other object **204** stowed in association with an item **106** may have one or more sensors **114** associated therewith. Sensors **114** may include force sensors, which may be used to determine characteristics of one or more forces applied to an item **106**. Sensors **114** may also include position sensors, which may be used to determine one or more of: the location of one or more portions of the body of a human operator **108** relative to an item **106** or the location of the item **106** relative to the human operator **108** or to other structures or objects **204**.

Sensor data **120** may include one or more force magnitudes **206**, which may represent the intensity of a force applied to an item **106** when a human operator **108** pushes, pulls, lifts, grips, or otherwise contacts the item **106**. A force magnitude **206** may be measured by one or more load cells, strain gauges, transducers, force sensitive resistors, pressure sensors, touch sensors, or other types of force sensors associated with a human operator **108**, item **106**, or manual manipulator used by a human operator **108**. In other implementations, force magnitude **206** may be determined from one or more images **118**. For example, the intensity with which a human operator **108** is applying a force may be determined from an image **118** depicting a pose of the body the human operator **108**, visible deformation in the body of the human operator **108** or the item **106**, and so forth.

Sensor data **120** may further include one or more force directions **208**. The direction of one or more forces applied to an item **106** may be measured using force sensors associated with the item **106**, a human operator **108** manipulating the item **106**, or a manual manipulator used by the human operator **108**. In some implementations, force directions **208** may be determined using one or more position sensors. For example, position sensors may determine a direction in which a hand or other portion of the body of a human operator **108** is moving when manipulating an item **106**. In other implementations, force directions **208** may be determined from one or more images **118**. For example, a direction in which a human operator **108** is applying a force to an item **106** may be determined from an image **118** depicting a pose of the body of the human operator **108** or multiple images **118** depicting movement of the human operator **108**. A force magnitude **206** and force direction **208** associated with a force together define a force vector **112**.

Sensor data **120** may also include position data **210**. Position data **210** may include data measured by one or more position sensors regarding the position of one or more portions of a human operator **108** or an item **106**. For example, the specific position of each finger of a human operator **108** may be measured by associating position sensors therewith. In one implementation, a human operator **108** may wear a glove or similar clothing article having one or more sensors **114** integrated therewith. Any portion of the body of a human operator **108**, an item **106**, or a manual manipulator used by a human operator **108** may have one or more proximity sensors, touch sensors, RFID or NFC sensors, orientation sensors, 3D sensors, location sensors, or another type of position sensor associated therewith, such that position of the human operator **108** relative to the item **106** may be determined.

Sensor data **120** may also include proximity data **212**. Proximity data **212** may be measured by one or more proximity sensors associated with the human operator **108**, the item **106**, a container **202** configured to contain the item **106**, one or more portions of a facility, and so forth. For example, proximity sensors may be used to determine whether a robotic manipulator **104** is positioned relative to an item **106** in a manner that will enable the robotic manipulator **104** to contact and manipulate the item **106**. Proximity sensors may be used to detect the presence of items **106** and robotic manipulators **104** within various locations of a facility.

Other sensor data **214** may include data received from other types of sensors **114**, such as light or temperature sensors, biomedical sensors, location sensors, and so forth. For example, a robotic manipulator **104** may be inoperable at certain temperature ranges or at certain locations determined using location sensors.

Constraint data **130** may include one or more truth sets or similar types of data relating to characteristics of a robotic manipulator **104**, one or more items **106**, a container **202**, a facility, rule sets (e.g., physics-based constraints) applicable to multiple environments, and so forth. For example, a robotic manipulator **104** may have a limited range of motion or may be unsuitable for handling certain types of items **106**. In other implementations, the dimensions of at least a portion of a robotic manipulator **104** may exceed available clearance in a location, such that the robotic manipulator **104** may not be used in that location. In still other implementations, one or more characteristics of an item **106**, such as fragility, may render the item **106** unsuitable for manipulation by a robotic manipulator **104**. A constraint module **128** may determine one or more constraints from the constraint data **130**. Determination of constraints may cause modification of one or more determined configurations **102**, deletion of certain configurations **102**, and so forth.

Constraint data **130** may include a manipulator range of motion **216**. While some robotic manipulators **104** may have a form and a range of motion comparable to that of a human hand, in some implementations, a robotic manipulator **104** may have fewer than five appendages or may have a shorter range of motion than that of a human hand. Constraints determined from the manipulator range of motion **216** may be used to modify or delete configurations **102** that would require a robotic manipulator **104** to move in a manner that exceeds the functional capabilities of the robotic manipulator **104**. Constraints determined from the manipulator range of motion **216** may further be used to generate configurations **102** suitable for manipulating an item **106**, using the item data **134** and data obtained from images **118** depicting interactions between human operators **108** and the item **106**.

The constraint data **130** may include manipulator equipment **218**. For example, robotic manipulators **104** may include one or more of the following: an anthropomorphic hand, one or more finger-like digits, a movable platform member, a vacuum-based gripping member, a suction-based gripping member, an adhesive-based gripping member, a friction-based gripping member, a ferromagnetic-based gripping member, and so forth. Constraints determined from the manipulator equipment **218** may be used to modify or delete configurations **102** that would require a robotic manipulator **104** to contact an item **106** in a manner that is not possible based on the gripping elements associated with the robotic manipulator **104**. Constraints determined from the manipulator equipment **218** may further be used to generate configurations **102** suitable for manipulating an item **106**.

The constraint data **130** may further include manipulator dimensions **220**. For example, the size of one or more portions of a robotic manipulator **104**, such as an arm and gripping portion thereof, may be used to determine whether all or a portion of the robotic manipulator **104** may pass within a clearance between an item **106** and surfaces of a container **202** or between the item **106** and an adjacent object **204**. Constraints determined from the manipulator dimensions **220** may be used to modify or delete configurations **102** that would require passage of the robotic manipulator **204** in areas with insufficient clearance.

Constraint data **130** may also include one or more manipulator locations **222**. For example, one or more locations within a facility may be inaccessible to robotic manipulators **104**. Configurations **102** for retrieving items **106** stored in such locations may be modified such that passage of the robotic manipulator **104** through the location(s) is not required. In some implementations, an indication of such a constraint that renders use of a robotic manipulator **104** impossible may be provided to a device associated with a human operator **108** to facilitate completion of the operation by a human.

Constraint data **130** may include item durability **224**. The durability of an item **106** may be determined from the item data **134**, from one or more images **118** depicting the item **106**, or from one or more sensors **114**. For example, certain types of items **106**, such as items **106** formed from fragile materials, may be unsuitable for manipulation by a robotic manipulator **104**. In some implementations, one or more indications regarding such a constraint may be provided to a device associated with a human operator **108** to facilitate completion of the operation by a human. In other implementations, constraints associated with item durability **224** may be used to generate configurations **102** for use with a robotic manipulator **104**. For example, constraints associated with item durability **224** may affect the maximum force magnitude **206** that may be applied to at least a portion of an item **106**.

Constraint data **130** may also include one or more item sizes/shapes **226**. In some implementations, items **106** having certain shapes, such as irregular shapes, or certain dimensions may be determined to be unsuitable for manipulation by a robotic manipulator **104**. For example, an item **106** that is too small to be gripped by a robotic manipulator **104** would be unsuitable for use therewith. In some implementations, one or more indications regarding such a constraint may be provided to a device associated with a human operator **108** to facilitate completion of the operation by a human. In other implementations, constraints relating to item sizes/shapes **226** may be used to generate configurations **102** suitable for use interacting with the item **106**.

Constraint data **130** may include one or more physics-based constraint(s) **228**. For example, one or more configurations **102** that may be executed using one or more robotic manipulators **104** may result in dropping of the item **106** or damage to the item **106** or robotic manipulator(s) **104** due to physics-based limitations. Continuing the example, a determined set of points of contact **110** may be usable by a robotic manipulator **104** without damaging an item **106**, but transport of the item **106** using the points of contact **110** may cause the item to become unstable. As such, physics-based constraints **228** may be used to modify or delete one or more configurations **102** that are not possible to be executed successfully. For example, responsive to a determination of a physics-based constraint **228**, a configuration **102** may be modified to increase the surface area of one or more points of contact **110** between a robotic manipulator **104** and an item **106**, to space the points of contact **110** between a robotic manipulator **104** and an item **106** more widely or more closely, and so forth.

Other constraint data **230** may include constraints relating to characteristics of a facility that may limit possible uses or movement of robotic manipulators **104**, characteristics of containers **202** containing items **106**, characteristics of other objects **204** that may limit possible uses or movement of robotic manipulators **104**, a maximum weight of an item **106** that may be manipulated by the robotic manipulator **104**, and so forth.

Item data **134** may include one or more physical characteristics associated with an item **106**. The item data **134** may be used to determine suitable points of contact **110** and force vectors **112** for manipulating the item **106**. Item data **134** may also be used to determine whether contacting certain portions of the item **104** or applying a force in excess of a certain force magnitude **206** may damage the item **106**.

Item data **134** may include the weight **232** of an item **106**. The weight **232** of the item **106** may be determined by weighing the item **106** prior to stowage or retrieval thereof. In some implementations, the weight **232** of the item **106** may be known or provided by a manufacturer or vendor thereof. In other implementations, the weight **232** of the item **106** may be determined from one or more images **118**. For example, the pose of a human operator **108** carrying an item **106**, depicted in an image **118**, may enable a possible weight range or approximate weights **232** of the item **106** to be determined. In some implementations, an item **106** may be classified as "light" or "heavy," based on the pose of a human operator **108**. For example, an item **106** held by a human operator **108** in a single hand, with the human operator's **108** feet beneath the shoulders may be determined to be light. An item **106** held by a human operator **108** with two hands, braced against the human operator's **108** arms and torso, while the human operator's **108** legs are bent may be determined to be heavy. The weight **232** of the item **106** may be used to determine forces necessary to lift and move the item **106** by the robotic manipulator **104**. In some implementations, the constraint data **130** may include a maximum weight **232** for an item **106** that may be manipulated by the robotic manipulator **104**.

The item data **134** may include dimensions **234** of the item **106**. Dimensions **234** may include length, width, height, depth, diameter, circumference, surface area, and so forth. Dimensions **234** of an item **106** may be determined by measuring the item **106** prior to stowage or retrieval thereof. In some implementations, the dimensions **234** of the item **106** may be known or provided by a manufacturer or vendor thereof. In other implementations, the dimensions **234** of the item **106** may be determined from one or more images **118** in which the item **106** is depicted. The dimensions **234** of the item **106** may be used to determine points of contact **110** that may be used to support the item **106** during movement thereof by the robotic manipulator **104**.

The item data **134** may further include a weight distribution **236** associated with the item **106**. For example, depending on the materials from which the item **106** is formed, the dimensions **234** or shape of the item **106**, and so forth, the weight **232** of the item **106** may be distributed across its dimensions **234** in a manner that a center of mass for the item **106** may be determined. The weight distribution **236** may be used to determine points of contact **110** and force vectors **112** that may be used to balance the item **106** during movement thereof by the robotic manipulator **104**.

The item data **134** may also include material characteristics **238** of the item **106**. Material characteristics **238** may include the materials from which one or more portions of the item **106** are formed, the durability (e.g., durometer measurement) or fragility of one or more portions of the item **106**, the flexibility or compressibility of one or more portions of the item **106**, and so forth. Material characteristics **238** may also facilitate determination of the weight distribution **236**, based on the location, weight, and density of one or more materials within the item **106**. The material characteristics **238** of an item **106** may determine one or more points of contact **110** and associated force vectors **112** that may be applied by a robotic manipulator **104** without damaging an item. In some implementations, the material characteristics **238** may be used to

determine whether the fragility or flexibility of an item **106** may prevent manipulation thereof by a robotic manipulator **104**.

The item data **134** may include a shape **240** corresponding to the item **106**. Shapes **240** of items **106** may include cuboids, spheroids, toroids, regular polygonal prisms, planar shapes, irregular planar and polygonal shapes, and so forth. The shape **240** of an item **106** may facilitate determination of the weight distribution **236** thereof. In some implementations, the shape **240** of an item **106** may be used to determine whether the item **106** is unsuitable for manipulation by a robotic manipulator **104**. For example, an item **106** having an irregular shape **240** with multiple protrusions may become damaged (e.g., crushed, dented, or otherwise broken) if handled by a robotic manipulator **104**. The shape **240** of an item **106** may facilitate determination of one or more points of contact **110** suitable for supporting the item **106** during manipulation thereof by a robotic manipulator **104**.

Other item data **242** may include other physical characteristics of an item **106**, such as an item state (e.g., solid, liquid, gas) of one or more portions of an item **106**, an item temperature, and so forth. Other item data **242** may further include whether the materials from which an item **106** is formed may be manipulated using suction-based, ferromagnetic-based, or friction-based gripping elements, the characteristics of an exterior surface of an item **106**, and so forth.

FIG. **3** illustrates a block diagram **300** of a computing device **302** configured to support operation of the system **100**. The computing device **302** may include one or more servers **122**, one or more robotic manipulators **104**, one or more cameras **116** or other types of sensors **114**, or other computing devices **302** in communication therewith. Computing devices **302** may further include computer-readable storage media (CRSM) or libraries accessible to the server(s) **122**, robotic manipulator(s) **104**, sensors **114**, or other computing devices **302**.

One or more power supplies **304** may be configured to provide electrical power suitable for operating the components in the computing device **302**. In some implementations, the power supply **304** may include a rechargeable battery, fuel cell, photovoltaic cell, power conditioning circuitry, and so forth.

The computing device **302** may include one or more hardware processors **306** (processors) configured to execute one or more stored instructions. The processor(s) **306** may include one or more cores. The processor(s) **306** may be application processing units (APUs), digital signal processors (DSPs), or graphics processing units (GPUs). One or more clocks **308** may provide information indicative of date, time, ticks, and so forth. For example, the processor(s) **306** may use data from the clock **308** to generate a timestamp, trigger a preprogrammed action, and so forth.

The computing device **302** may include one or more communication interfaces **310**, such as input/output (I/O) interfaces **312**, network interfaces **314**, and so forth. The communication interfaces **310** may enable the computing device **302**, or components thereof, to communicate with other devices or components. The I/O interfaces **312** may include interfaces such as Inter-Integrated Circuit (I2C), Serial Peripheral Interface bus (SPI), Universal Serial Bus (USB) as promulgated by the USB Implementers Forum, RS-232, and so forth.

The I/O interface(s) **312** may couple to one or more sensors **114** or other types of I/O devices. I/O devices may include any manner of input device or output device associated with the server(s) **122**, robotic manipulator(s) **104**, sensors **114**, or other computing device **302**. For example, the sensors **114** may include cameras **116** or other types of image sensors, one or more force sensors **316**, position sensors **318**, touch sensors **320**, proximity sensors **322**, or location sensors **324**. Other I/O devices **326** may include other types of sensors **114**, such as light sensors, 3D sensors, temperature sensors, and so forth. Other I/O devices **326** may include devices used to interact with computing devices **302**, such as buttons, keyboards, mouse devices, scanners, displays, haptic devices, printers, microphones, speakers and so forth. In some implementations, sensors **114** and I/O devices may be physically incorporated with the computing device **302** or may be externally placed.

The network interfaces **314** may be configured to provide communications between the computing device **302** and other devices, such as the sensors **114**, I/O devices, routers, access points, and so forth. The network interfaces **314** may include devices configured to couple to one or more networks including LANs, wireless LANs, WANs, wireless WANs, and so forth. For example, the network interfaces **314** may include devices compatible with Ethernet, Wi-Fi®, Bluetooth®, ZigBee®, Z-Wave, 3G, 4G, LTE, and so forth.

The computing device **302** may include one or more busses or other internal communications hardware or software that allows for the transfer of data between the various modules and components of the computing device **302**.

As shown in FIG. **3**, the computing device **302** may include one or more memories **328**. The memory **328** may include one or more CRSM. The CRSM may be any one or more of an electronic storage medium, a magnetic storage medium, an optical storage medium, a quantum storage medium, a mechanical computer storage medium, and so forth. The memory **328** may provide storage of computer-readable instructions, data structures, program modules, and other data for the operation of the computing device **302**. A few example modules are shown stored in the memory **328**, although the same functionality may alternatively be implemented in hardware, firmware, or as a system on a chip (SoC).

The memory **328** may include one or more operating system (OS) modules **330**. The OS module **330** may be configured to manage hardware resource devices such as the I/O interfaces **312**, the network interfaces **314**, the sensors **114**, one or more I/O devices, and to provide various services to applications or modules executing on the processors **306**. The OS module **330** may implement a variant of the FreeBSD™ operating system as promulgated by the FreeBSD Project; UNIX™ or a UNIX-like operating system; a variation of the Linux™ operating system as promulgated by Linus Torvalds; the Windows® operating system from Microsoft Corporation of Redmond, Wash., USA; or other operating systems.

A data store **332** and one or more of the following modules may also be stored in the memory **328**. The modules may be executed as foreground applications, background tasks, daemons, and so forth. The data store **332** may use a flat file, database, linked list, tree, executable code, script, or other data structure to store information. In some implementations, the data store **332** or a portion of the data store **332** may be distributed across one or more other devices including the computing devices **302**, network attached storage devices, and so forth.

A communication module **334** may be configured to establish communications with one or more other computing devices **302**, such the server(s) **122**, robotic manipulator(s) **104**, sensors **114**, one or more remote CRSM, and so forth. The communications may be authenticated, encrypted, and so forth.

The memory **328** may store the image processing module **124**. The image processing module **124** may access one or more images **118** received from cameras **116** or other image

sensors and determine points of contact **110**, force vectors **112**, constraints, and so forth, from the image(s) **118**. As described previously, image processing may be performed using the OpenCV library, Willow Garage, Itseez, or other image processing tools. In some implementations, image processing may include segmenting images **118** by sampling portions thereof and computing one or more Histograms of Oriented Gradients (HoG) over different color channels. The size of the image portions sampled may be determined by the dimensions **234** of all or a portion of an item **106**, container **202**, or human operator **108**.

The memory **328** may also store the sensor processing module **126**. The sensor processing module **126** may access sensor data **120** received from one or more sensors **114**. For example, the sensor processing module **126** may convert measurements received from one or more force sensors **316** to one or more of a point of contact **110**, a force magnitude **206**, a force direction **208**, or a force vector **112**. Continuing the example, the sensor processing module **126** may convert measurements received from one or more position sensors **318** or other types of sensors **114** to data usable to determine a point of contact **110**, a force vector **112**, and so forth.

The memory **328** may further store the constraint module **128**. The constraint module **128** may access constraint data **130**, which may include limitations relating to robotic manipulator(s) **104**, item(s) **106**, containers **202**, facilities, other objects **204** proximate to the item **106**, physics-based constraints **228**, and so forth. Based on one or more of the images **118**, sensor data **120**, constraint data **130**, item data **134**, or location data **136**, the constraint module **128** may determine one or more constraints regarding use of the robotic manipulator(s) **104** with one or more items **106**. Determined constraints may be used to modify or delete one or more configurations **102**. For example, a robotic manipulator **104** lacking a number of appendages sufficient to duplicate a grip of a human operator **108** (e.g., having five fingers) may execute a configuration **102** having a smaller number of points of contact **110**, spaced in a manner to simulate the grip of a five-fingered hand of a human operator **108**. The force vectors **112** applied at each point of contact **110** may be greater than those applied by a human operator **108** due to the smaller number of points of contact **110** present in the configuration **102** for the robotic manipulator **104**. In another example, the constraints determined for a robotic manipulator **104** having a gripping mechanism unable to grip compressible or flexible items **106** may prevent execution of any configuration **102** for gripping a flexible or compressible item **106** by the robotic manipulator **104**. In some implementations, an indication may be provided to a device associated with a human operator **108** to facilitate completion of a stowage or retrieval operation of a flexible or compressible item **106** by a human.

The memory **328** may also store the configuration generating module **132**. The configuration generating module **132** may access data generated by the image processing module **124** from the one or more images **118**, sensor data **120** processed by the sensor processing module **126**, one or more constraints determined by the constraint module **128** using the constraint data **130**, and the item data **134**. The accessed data may be used to determine one or more configurations **102** by which the robotic manipulator(s) **104** may interact with one or more items **106**.

Using points of contact **110** and force vectors **112** determined from the images **118** and sensor data **120**, the configuration generating module **132** may determine an initial set of configurations **102** for execution by the robotic manipulator **104**. Constraints determined from the constraint data **130** and the item data **134** may be used to determine configurations **102** that may not be possible to execute using the robotic manipulator **104**. Such configurations **102** may be modified or deleted, such that the resulting set of configurations **102**, modified by one or more constraints, may be used by the robotic manipulator **104** to successfully interact with the item **106**. The images **118**, sensor data **120**, and item data **134** may further be used to generate a model of interactions between an item **106** and a robotic manipulator **104**. The constraint data **130** may be used to determine one or more configurations **102** of the robotic manipulator **104** suitable for use with the item **106**. For example, the points of contact **110** and force vectors **112** applied to an item **106** by human operators **108** may be unusable by a robotic manipulator **104**. However, the images **118** and sensor data **120** associated with the interactions between the human operators **108** and the item **106** may be used to determine characteristics of the item **106**, such as a shape **240**, dimensions **234**, weight **232**, weight distribution **236**, and material characteristics **238**. From these characteristics and the constraint data **130**, the configuration generating module **132** may determine configurations **102** suitable for use by the robotic manipulator **104** that may differ from the points of contact **110** and force vectors **112** applied to the item **106** by a human operator **108**.

In some implementations, the location data **136** may be used to determine one or more constraints that may be used to modify or prevent execution of one or more configurations **102**. For example, one or more locations in which an item **106** is stored may be inaccessible to a robotic manipulator **104**. In some implementations, a first configuration **102** may be more suitable for use at a first location such as a mostly-empty shelf, while a second configuration **102** is more suitable for use at a second location such as a mostly-full crate.

A manipulator control module **336** is also shown in the memory **328**. The manipulator control module **336** may be used to access and control one or more robotic manipulators **104** responsive to requests to store, retrieve, or otherwise move or manipulate one or more items **106**. For example, the manipulator control module **336** may access a request to move an item **106** received from another computing device **302**. Responsive to this request, the manipulator control module **336** may access location data **136** in the data store **332** corresponding to the item **106** to determine a current location of the item **106**. In some implementations, the location data **136** may include a destination location for the item **106**. The manipulator control module **336** may cause movement of the robotic manipulator **104** to the location of the item **106**, movement of the item **106** to the location of the robotic manipulator **104**, or movement of both the robotic manipulator **104** and the item **106** to positions configured to enable contacting the item **106** with the robotic manipulator **104**.

The manipulator control module **336** may cause the robotic manipulator **104** to contact the item **106** using the point(s) of contact **110** and force vector(s) **112** of a determined configuration **102**. In some implementations, an image **118** of the current location of the item **106** may be accessed, and one configuration **102** of a plurality of configurations **102** may be determined for use based on the current location of the item **106**. For example, the orientation of the item **106** within a container **202** or the position of the item **106** relative to other objects **204** may cause use of one configuration **102** to be suitable, while one or more other configurations **102** may be rendered impossible or less likely to successfully manipulate the item **106**. In some implementations, one or more configurations **102** may include a reference position of the item **106**. For example, a configuration **102** may include points of contact **110** or force vectors **112** that may be applied to the item

106 when it is upright. The manipulator control module **336** may determine the orientation of an item **106**, such as through use of one or more images **118** thereof. The manipulator control module **336** may also position one or more of the robotic manipulator **104** or the item **106** such that the item **106** is placed in the reference position relative to the robotic manipulator **104**. The configuration **102** may then be used to contact the item **106** using the robotic manipulator **104**.

After contacting an item **106** using a robotic manipulator **104**, such as by gripping, lifting, supporting, or otherwise moving the item **106**, the manipulator control module **336** may cause the robotic manipulator **104** to move the item **106** from a first location to a second location. For example, a robotic manipulator **104** may be used to move an item **106** from a receiving area of a facility to a location within an interior of a container **202**. A robotic manipulator **104** may be used to move an item **106** from a container **202** or other storage area of a facility to a location suitable for transport. In some implementations, a robotic manipulator **104** may be used to move one or more items **106** or containers **202** from a first location within a facility to a second location within the facility.

Other modules **338** may also be present in the memory **328**. For example, encryption modules may be used to encrypt and decrypt communications between computing devices **302**. User interface modules may be used to enable users to interact with computing devices **302**, to modify data in the data store **332**, to input data or parameters regarding items **106**, robotic manipulators **104**, storage containers **202**, and so forth. Output generation modules may be used to provide confirmations, indications of completed processes, indications of processes to be performed by human operators **108**, and so forth. Other data **340** may be stored in the data store **332** and may include encryption data, layouts of all or a portion of a facility, data regarding containers **202**, data regarding operating conditions and parameters of robotic manipulators **104**, and so forth.

In some implementations, different computing devices **302** may have different capabilities or capacities. For example, the server(s) **122** may have significantly more processor **306** capability and memory **328** capacity compared to the robotic manipulator(s) **104** or sensors **114**.

FIG. **4** depicts a scenario **400** for generating one or more configurations **102** for a robotic manipulator **104** to contact an item **106**. The configurations **102** may be generated using data obtained from a human operator **108**.

At **402**, one or more points of contact **110** between a human operator **108** and an item **106** may be determined from one or more images **118**. For example, one or more servers **122** or other computing devices **302** may access one or more stored images **118**. Alternatively, one or more images **118** may be received from a camera **116** or other types of image sensors. An image processing module **124** associated with the server(s) **122** or other computing devices **302** may determine one or more of the following: points of contact **110** between the body of the human operator **108** and the item **106**, points of contact **110** between a manual manipulator used by the human operator **108** and the item **106**, characteristics of the item **106** based on the pose of the human operator **108**, characteristics of the item **106** based on the physical appearance of the item **106**, one or more forces applied to the item **106** by the human operator **108**, a location where the human operator **108** and item **106** were positioned at the time the image **118** was generated, and so forth.

At **404**, one or more force vectors **112** applied by the human operator **108** to the item **106** may be determined using one or more sensors **114**. For example, the hand or other body portion of the human operator **108**, the item **106**, or both the human operator **108** and the item **106** may be instrumented with one or more of the following: force sensors **316** or position sensors **318**. The sensors **114** may determine the magnitude, the direction, or both the magnitude and direction of one or more forces applied by the human operator **108** to the item **106**. Sensor data **120** generated by the sensors **114** may be provided to the server(s) **122** or other computing devices **302**. A sensor processing module **126** may process the sensor data **120** to determine one or more force vectors **112** applied to the item **106**. In some implementations, one or more force vectors **112** may be determined based on a rate of movement of the human operator **108** or the item **106**. In other implementations, one or more possible force vectors **112** may be determined based on visible or measurable compression of a portion of the body of the human operator **108** or the item **106**. One or more of the human operator **108** or the item **106** may be equipped with sensors **114** to facilitate measurement of such compression or deformation. Sensors **114** may also generate sensor data **120** that may be used to determine a current location of the human operator **108** or the item **106**, proximity of the human operator **108** or item **106** to locations or objects **204** instrumented with proximity sensors **322**, temperature, pressure, or humidity at the location of the human operator **108** or item **106**, whether packaging of the item **106** has become opened or damaged, and so forth.

At **406**, one or more physical characteristics of the item **106** may be determined from item data **134**. Item data **134** may be stored in one or more servers **122** or other computing devices **302**. In some implementations, physical characteristics of an item **106** may be determined and stored when an item **106** is received or stowed at a facility. For example, an item **106** may be weighed, measured, or otherwise analyzed prior to placement in a container **202**. In other implementations, physical characteristics of an item **106**, such as the weight **232**, dimensions **234**, material characteristics **238**, and so forth, may be provided by a manufacturer or vendor associated with the item **106**. In some implementations, characteristics of an item **106** may be determined from one or more images **118** that depict the item **106** or one or more sensors **114** associated with the item **106**. For example, handling of an item **106** by a robotic manipulator **104** or a human operator **108** having sensors **114** associated therewith may be used to determine a weight **232**, weight distribution **236**, shape **240**, material characteristics **238**, or dimensions **234** of an item **106**. Item data **134** may be used to determine one or more configurations **102** suitable for gripping, lifting, or otherwise manipulating the item **106**. In the depicted scenario **400**, the dimensions **234**, weight **232**, shape **240**, weight distribution **236** (e.g., center of mass), and material characteristics **238** of the item **106** are depicted as item data **134**.

At **408**, one or more constraints associated with a robotic manipulator **104** or the item **106** may be determined from constraint data **130**. For example, the server(s) **122** are shown accessing constraint data **130** from a data store **332** that includes eight possible shapes **240** of items **106**. Four of the depicted shapes **240** may be suitable for manipulation by a robotic manipulator **104**, while the other four of the depicted shapes **240** may be unsuitable for manipulation by the robotic manipulator **104**. The depicted constraint data **130** also includes a limitation regarding a maximum weight **232** of the item **106** (e.g., less than ten pounds), and a restriction regarding the material characteristics **238** of the item **108** (e.g., the item may not be made from glass.) While the depicted scenario **400** includes constraint data **130** relating to the shape **240**, weight **232**, and material characteristics **238** of an item **106**, constraints may also be determined based on character-

istics of the robotic manipulator **104**, the facility or other location, or physics-based constraints **228**. For example, constraints may be based on the manipulator range of motion **216**, the manipulator equipment **218**, the manipulator dimensions **220**, manipulator locations **222** that may be inaccessible to a robotic manipulator **104**, item durability **224**, one or more physics-based constraints **228**, and so forth. In the depicted scenario **400**, the shape **240** of the item **106** noted in the item data **134** is rectangular, the weight **232** of the item **106** is seven pounds, and the material characteristics **238** of the item **106** include use of wood and plastic. The constraint data **130** may indicate that items **106** having a rectangular shape **240**, a weight **232** less than ten pounds, and materials other than glass are suitable for manipulation using a robotic manipulator **104**.

At **410**, one or more configurations **102** for the robotic manipulator **104** to contact the item **106** may be generated. Generated configurations **102** may be provided to one or more robotic manipulators **104** by the server(s) **122** or other computing devices **302**. For example, the server(s) **122** or other computing devices **302** may use the determined point(s) of contact **110** and force vector(s) **112** to generate a corresponding set of point(s) of contact **110** and force vector(s) **112** usable by the robotic manipulator **104**. The point(s) of contact **110** and force vector(s) **112** of the configuration **102** for the robotic manipulator **104** may not necessarily be identical to the point(s) of contact **110** and force vector(s) **112** used by the human operator **108**. For example, a robotic manipulator **104** may lack a manipulator range of motion **216** comparable to the range of motion of the hand of a human operator **108**. Similarly, a robotic manipulator **104** may lack manipulator equipment **218** similar in form and function to a human hand. Constraints relating to the functionality of the robotic manipulator **104** may be used to determine configuration **102** modifications to the points of contact **110** and force vectors **112** determined from the image **118** that may still successfully manipulate an item **106**. In some implementations, constraint data **130** and a model of an item **106** determined from item data **134** and one or more images **118** may be used to generate configurations **102** having points of contact **110** and force vectors **112** that differ significantly from those used by human operators **108** to manipulate items **106**.

FIG. **5** is a scenario **500** for determining one or more constraints that may prevent a robotic manipulator **104** from accessing an item **106**. At **502**, a request **504** associated with placement of an item **106** may be received from a computing device **302**. For example, a first computing device **302(1)** is shown providing a request **504** to one or more server(s) **122**. A request **504** may include instructions to store an item **106** at a storage location, such as within a container **202** at a facility. In other implementations, a request **504** may include instructions to retrieve a stored item **106**, such as an item **106** currently stored within a container **202** at a facility. In the depicted scenario **500**, the request **504** provided by the device **302(1)** may be generated responsive to a user associated with the device **302(1)** purchasing the item **106**.

At **506**, location data **136** associated with the item **106** and one or more images **118** of a current location of the item **106** may be accessed from the server **122**. In the depicted scenario **500**, the location data **136** includes an identification of a section within a facility where the item **106** may be stored. The section may correspond to a particular container **202** within the facility. In other implementations, location data **136** may include GPS coordinates, a map location, a physical address, a distance and direction relative to the device accessing the location data **136**, and so forth. The server(s) **122** are depicted accessing an image **118** that depicts the item **106** within a container **202**, such as a box, bin, crate, and so forth. Three other objects **204** are positioned adjacent to the item **106** within the container **202**. While the container **202** is depicted having a rectangular shape, any manner of container **202** may be used. In some implementations, an item **106** may be stored at a location external to a container **202**.

At **508**, constraint data **130** relating to an interaction between a robotic manipulator **104** and the item **106** may be accessed. For example, the constraint data **130** may include limitations regarding a manipulator range of motion **216**, manipulator equipment **218**, manipulator dimensions **220**, manipulator locations **222**, and so forth, which may be inaccessible to a robotic manipulator **104**. In other implementations, constraint data **130** relating to characteristics of the item **106** may be accessed by the server(s) **122**. In the depicted scenario **500**, the robotic manipulator **104** is shown having manipulator dimensions **220** ("W1") associated with the manipulating end used to contact items **106**.

At **510**, one or more constraints that may prevent the robotic manipulator **104** from accessing the item **106** may be determined. For example, a width ("W2") between the item **106** and a surface of the container **202** may be determined from the image **118**. In some implementations, the image **118** may include depth information to facilitate determination of dimensions and distances using the image **118**. For example, the image **118** may be acquired using a depth camera. In the depicted scenario **500**, the width of the manipulator dimensions **220** ("W1") exceeds the width ("W2") between the item **106** and the surface of the container **202**. As such, the robotic manipulator **104** may be unable to pass into the container **202** adjacent to the item **106** to grip or otherwise access or manipulate the item **106**. As another example, the constraint data **130** may indicate that the portion of the item **106** that does not abut adjacent objects may include a fragile material, a degree of rigidity or compressibility, or a surface texture that would inhibit manipulation of the exposed portion of the item **106** by a robotic manipulator **104**.

At **512**, an indication **514** of the constraints preventing use of the robotic manipulator **104** may be provided to a device **506(2)** associated with a human operator **108**. In the depicted scenario **500**, the indication **514** provided to the human operator **108** may include an image **118** of the item **106** as it was packaged or stored to facilitate manual location of the item **106**. In the depicted scenario **500**, the human operator **108** may be provided with an image **118** depicting the container **202** containing the item **106**. For example, the image **118** may be projected on to a surface of the container **202** or displayed on a second computing device **302(2)** associated with the human operator **108**. In some implementations, the location of the item **106** within the image **118** may be highlighted or otherwise accentuated to facilitate the visibility thereof. Providing an image **118** displaying the item **106** in the location in which it was stored, such as the container **202** containing one or more other objects **204**, may improve efficiency and reduce errors of a human operator **108**.

FIG. **6** is a scenario **600** for using a configuration **102** for a robotic manipulator **104** to contact an item **106**. In the depicted scenario **600**, the configuration **102** may depend on the position of the item **106**. For example, a robotic manipulator **104** may be configured to contact, grip, lift, or otherwise manipulate an item **106** when the item **106** is in a particular position (e.g., orientation) relative to the robotic manipulator **104**. If the item **106** is in a different position, one or more of the robotic manipulator **104** or the item **106** may be moved relative to the other. For example, the robotic manipulator **104** may translate toward or away from the item **106** or rotate relative to the item **106**. Alternatively, the item **106** may be

moved toward or away from the robotic manipulator **104** or rotated relative to the robotic manipulator **104** by a human operator **108** or an automated device.

At **602**, a configuration **102** for contacting an item **106** using a robotic manipulator **104** may be accessed from a data store **322**. The configuration **102** may include a reference position of the item **106**. For example, in the depicted scenario **600** a robotic manipulator **104** is shown adjacent to an item **106** that is in a first position. The robotic manipulator **104** may access a configuration **102** based on the item **106** being in a second position different from the first position. The depicted configuration **102** includes a first point of contact **110**(**1**) and a second point of contact **110**(**2**) at the base of the item **106**. The configuration **102** also includes a first force vector **112**(**1**) associated with the first point of contact **110**(**1**) and a second force vector **112**(**2**) associated with a second point of contact **110**(**2**).

At **604**, a current position **606** of the item **106** relative to a reference position **608** of the item **106** that corresponds to the position of the item **106** in the configuration **102** may be determined. In the depicted scenario **600**, the robotic manipulator **104**, or a server **122** or other computing device **302** in communication therewith, may determine the current position **606** of the item **106**. For example, the current position **606** of the item **106** may be determined through use of a camera **116** or other type of sensor **114** associated with the robotic manipulator **104**, the item **106**, or the location of the item **106**. The current position **606** may be compared with a reference position **608**, which may be determined from the configuration **102**. The direction and distance the item **106** or robotic manipulator **104** must move so that the item **106** is positioned in the reference position **608** relative to the robotic manipulator **104** may be determined by this comparison.

At **610**, one or more of the robotic manipulator **104** or the item **106** may be moved such that the item **106** is in the reference position **608** relative to the robotic manipulator **104**. In the depicted scenario **600**, the robotic manipulator **104** has been rotated and secured to a perpendicular surface such that while the item **106** remained stationary, the item **106** is in the reference position **608** relative to the robotic manipulator **104**. In other implementations, the item **106** may be moved relative to the robotic manipulator **104**. Movement of the item **106** may be performed using the robotic manipulator **104**, a human operator **108**, or another device.

At **612**, the robotic manipulator **104** may contact the item **106** using the configuration **102**. For example, the robotic manipulator **104** may execute the configuration **102** to grip, lift, or otherwise move the item **106** from its reference position **608** by applying force vectors **112** to the points of contact **110** of the item **106** determined by the configuration **102**.

FIG. **7** is a flow diagram **700** illustrating a process for determining whether a configuration **102** for a robotic manipulator **104** may be used to move an item **106** based on the position of the item **106** within a container **202** relative to other objects **204**.

At **702**, a request **504** associated with placement of an item **106** may be received from a computing device **302**. The request **504** may include instructions to store an item **106** or to retrieve a stored item **106**. For example, if an item **106** stored at a facility is purchased, the request **504** may include an instruction to retrieve the item **106** from a location within the facility. Location data **136** corresponding to the item **106** may be used to determine a current location of the item **106**, and a robotic manipulator **104** or human operator **108** may move into proximity of the item **106**. In other implementations, a container **202** containing the item **106** may be moved into proximity of the robotic manipulator **104** or human operator **108**.

At **704**, a position of the item **106** relative to at least one object **204** may be determined using one or more images **118** indicative of the item **106** within a container **202**. In some implementations, one or more images **118** of the item **106** within the container **202** may be accessed from a data store **332**. For example, images **118** of a container **202** after storage of an item **106** therein may be generated at the time the item **106** is stored. In other implementations, one or more images **118** of the item **106** within the container **202** may be acquired using a camera **116** associated with a robotic manipulator **104**, human operator **108**, or a location at which the container **202** is currently located. An image processing module **124** may process the one or more images **118** to determine the position of the item **106** within the container **202**, relative to one or more other objects **204**.

At **706**, one or more configurations **102** for manipulation of the item **106** by a robotic manipulator **104** may be accessed from a server **122**. As described previously, configurations **102** may be generated using one or more of the following: images **118** depicting human operators **108** interacting with items **106**, sensor data **120**, constraint data **130**, item data **134**, or location data **136**. A configuration **102** may include one or more points of contact **110** between the robotic manipulator **104** and the item **106**. A configuration **102** may also include one or more force vectors **112** associated with the one or more points of contact **110**.

At **708**, one or more constraints may be determined using constraint data **130** and the position of the item **106** relative to the objects **204** within the container **202**. For example, the position of one or more objects **204** or the walls or other surfaces of the container **202** may prevent the robotic manipulator **104** from accessing the item **106**. Continuing the example, the manipulator dimensions **220** associated with the portion of the robotic manipulator **104** configured to contact the item **106** may exceed the clearance within the container **202**. In other circumstances, the item **106** may be accessible to a robotic manipulator **104** but oriented in a position that prevents successful execution of the configuration **102** by the robotic manipulator **104**, such as failing to properly grip or otherwise manipulate the item **106**. In some circumstances, the container **202** may be full or mostly full, the item **106** may not be readily visible or accessible, and the robotic manipulator **104** may not be configured to successfully move other objects **204** within the container **202**.

At **710**, a determination is made whether the constraint prevents use of the configuration **102** by the robotic manipulator **104**. When the constraint does not prevent use of the configuration **102**, then the process may proceed to **712**. At **712**, the robotic manipulator **104** may move the item **106** using the configuration **102**. For example, the robotic manipulator **104** may grip or support the item **106** at one or more points of contact **110** corresponding to the configuration **102**. The robotic manipulator **104** may also apply forces to the item **106** at the points of contact **110** corresponding to the force vectors **112** of the configuration **102**. The robotic manipulator **104** may be used to move the gripped or supported item **106** into or from a container **202**, to another location within a container **202** or facility, and so forth.

At **714**, one or more additional images **118** of the container **202** may be generated. For example, after the item **106** is removed from the container **202**, subsequent image(s) **118** may be generated to record the new state of the container **202**. If a future request **504** to move an object **204** within the

container **202** is received, the subsequent image(s) **118** may be used to determine constraints associated with movement of the object **204**.

Returning to the determination at **710**, when the constraint prevents use of the configuration **102**, then the process proceeds to **716**. At **716**, the one or more images **118** of the item **106** within the container **202** may be provided to a device **506** associated with a human operator **108**. Providing of the images **118** to the human operator **108** may facilitate manual location of the item **106** within the container **202**. In some implementations, the location of the item **106** within the image(s) **118** may be indicated, such as through use of an outline, highlighting, a selected color or intensity, and so forth.

FIG. **8** is a flow diagram **800** illustrating a process for generating a configuration **102** for contacting the item **106**, determining an accuracy metric associated with the configuration **102**, and modifying the configuration **102** based on the accuracy metric.

At **802**, one or more points of contact **110** between a manual manipulator (e.g., a human hand or a human-operated tool or device) and an item **106** may be determined from one or more images **118**. For example, an image processing module **124** may determine the position of the body of a human operator **108** relative to that of an item **106** to identify portions of the body of the human operator **108** that contact the item **106** and the portions of the item **106** that are contacted. In some implementations, sensor data **120** from one or more sensors **114** may also be used to determine points of contact **110** and force vectors **112** associated with the points of contact **110**.

At **804**, a configuration **102** for contacting the item **106** using a robotic manipulator **104** may be generated. The configuration **102** may be based on the determined points of contact **110** and on item data **134** relating to one or more physical characteristics of the item **106**. For example, the weight **232**, dimensions **234**, weight distribution **236**, material characteristics **238**, shape **240**, and so forth, of the item **106** may affect the forces that may be applied to various portions of the item **106** and suitable points of contact **110** for gripping or supporting the item **106**. The determinations made using the image(s) **118**, in combination with the item data **134**, may be processed by a configuration generation module **132** to determine suitable configurations **102** for interacting with the item **106** using a robotic manipulator **104**. In some implementations, constraint data **130** relating to limitations of the robotic manipulator **104**, limitations of the item **106**, or physics-based constraints **228** may also be used to generate the configuration **102**.

At **806**, the robotic manipulator **104** may be positioned relative to the item **106** and a container **202** configured to contain the item **106**. One or more of the robotic manipulator **104**, the item **106**, or the container **202** may be moved to place the robotic manipulator **104** into a position suitable to contact the item **104**. The item **106** may be within or external to the container **202**.

At **808**, the item **106** may be moved relative to the container **202** using the configuration **102**. For example, the robotic manipulator **104** may be used to grip, support, or otherwise manipulate the item **106**, to move the item **106** from the exterior of the container **202** to a location inside the container **202**. The robotic manipulator **104** may also be used to move the item **106** from the interior of the container **202** to a location external to the container **202**. In some implementations, the container **202** may contain other objects **204**.

At **810**, an accuracy metric associated with movement of the item **106** may be determined. For example, the configuration generating module **132** may determine one or more of the following: whether the robotic manipulator **104** successfully gripped or supported the item **106**, movement of the item **106** while being gripped or supported by the robotic manipulator **104**, whether the item **106** was dropped by the robotic manipulator **104**, whether the item **106** was damaged by contact with the robotic manipulator **104**, movement of the robotic manipulator **104** into and from the interior of the container **202**, or whether the container **202** was damaged by contact with the robotic manipulator **104** or the item **106**.

At **812**, the configuration **102** may be modified based on the accuracy metric. For example, if the item **106** moved significantly or was dropped by the robotic manipulator **104** due to insufficient friction between the robotic manipulator **104** and the item **106**, the configuration **102** may be modified to increase the force magnitude **206** of one or more force vectors **112**. If the item **106** moved significantly while gripped or supported by the robotic manipulator **104** or was dropped by the robotic manipulator **104** due to insufficient stability, the points of contact **110** may be changed, or the configuration **102** may be modified such that the robotic manipulator **104** moves more slowly. In some implementations, a horizontal support may be placed beneath the robotic manipulator **104** such that if the item **106** becomes disengaged from the robotic manipulator **104**, the support may prevent the item **106** from becoming damaged. For example, a basket or net may be suspended below the robotic manipulator **104**. The robotic manipulator **104** may be used to grip or otherwise engage the item **106** from the horizontal support surface to attempt to transfer the item into a container **202**. If the robotic manipulator **104** contacts the walls of the container **202** or other objects **204** in the container **202**, constraint data **130** may be generated to account for the manipulator dimensions **220**.

The processes discussed herein may be implemented in hardware, software, or a combination thereof. In the context of software, the described operations represent computer-executable instructions stored on one or more computer-readable storage media that, when executed by one or more hardware processors, perform the recited operations. Generally, computer-executable instructions include routines, programs, objects, components, data structures, and the like that perform particular functions or implement particular abstract data types. Those having ordinary skill in the art will readily recognize that certain steps or operations illustrated in the figures above may be eliminated, combined, or performed in an alternate order. Any steps or operations may be performed serially or in parallel. Furthermore, the order in which the operations are described is not intended to be construed as a limitation.

Embodiments may be provided as a software program or computer program product including a non-transitory computer-readable storage medium having stored thereon instructions (in compressed or uncompressed form) that may be used to program a computer (or other electronic device) to perform processes or methods described herein. The computer-readable storage medium may be one or more of an electronic storage medium, a magnetic storage medium, an optical storage medium, a quantum storage medium, and so forth. For example, the computer-readable storage media may include, but is not limited to, hard drives, floppy diskettes, optical disks, read-only memories (ROMs), random access memories (RAMs), erasable programmable ROMs (EPROMs), electrically erasable programmable ROMs (EEPROMs), flash memory, magnetic or optical cards, solid-state memory devices, or other types of physical media suitable for storing electronic instructions. Further, embodiments may

also be provided as a computer program product including a transitory machine-readable signal (in compressed or uncompressed form). Examples of transitory machine-readable signals, whether modulated using a carrier or unmodulated, include, but are not limited to, signals that a computer system or machine hosting or running a computer program can be configured to access, including signals transferred by one or more networks. For example, the transitory machine-readable signal may comprise transmission of software by the Internet.

Separate instances of these programs can be executed on or distributed across any number of separate computer systems. Thus, although certain steps have been described as being performed by certain devices, software programs, processes, or entities, this need not be the case, and a variety of alternative implementations will be understood by those having ordinary skill in the art.

Additionally, those having ordinary skill in the art readily recognize that the techniques described above can be utilized in a variety of devices, environments, and situations. Although the subject matter has been described in language specific to structural features or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described. Rather, the specific features and acts are disclosed as exemplary forms of implementing the claims.

What is claimed is:

1. A system comprising:

a robotic manipulator;

a non-transitory computer-readable medium storing computer-executable instructions; and

a hardware processor configured to execute the computer-executable instructions to:

access a plurality of images indicative of interactions between one or more human operators and an item;

determine at least one point of contact between the one or more human operators and the item using the plurality of images;

access force data received from one or more sensors associated with one or more of the one or more human operators or the item, wherein the force data corresponds to one or more force vectors applied by the one or more human operators to the item;

access item data comprising at least one physical characteristic of the item;

access constraint data relating to one or more of the robotic manipulator or the at least one physical characteristic of the item;

generate at least one configuration of the robotic manipulator based at least partially on the plurality of images, the force data, and the constraint data, wherein the at least one configuration comprises:

one or more points of contact between the robotic manipulator and the item; and

one or more force vectors associated with at least a portion of the one or more points of contact;

receive a request associated with placement of the item;

access location data associated with the item;

position one or more of: the item relative to the robotic manipulator or the robotic manipulator relative to the item to enable movement of the item by the robotic manipulator;

contact one or more portions of the item with the robotic manipulator, wherein the one or more portions of the item correspond to the one or more points of contact of the at least one configuration;

apply one or more forces to at least a subset of the one or more portions of the item with the robotic manipulator, wherein the one or more forces correspond to the one or more force vectors of the at least one configuration; and

move the item from a first location to a second location using the robotic manipulator.

2. The system of claim **1**, further comprising computer-executable instructions to:

access an image indicative of the item within a container;

determine a position of the item within the container using the image, wherein the determined position of the item within the container is used to position the one or more of the item or the robotic manipulator; and

generate an additional image indicative of the container subsequent to movement of the item.

3. The system of claim **1**, further comprising computer-executable instructions to:

access at least one image indicative of one or more of: the item or a human body associated with the one or more human operators; and

determine, using the at least one image, one or more of: an orientation of the item, the one or more force vectors applied to the item by the human body, or the one or more points of contact between the human body and the item.

4. The system of claim **1**, further comprising computer-executable instructions to:

access at least one image of the plurality of images indicative of a current location of the item relative to at least one additional object; and

determine, using the at least one image, at least one constraint relating to one or more of: passage of at least a portion of the robotic manipulator between the item and the at least one additional object, or manipulation of the item relative to the at least one additional object;

wherein generating the at least one configuration of the robotic manipulator is further based at least partially on the at least one constraint.

5. A method comprising:

accessing at least one image indicative of a manual manipulator contacting an item;

determining one or more points of contact between the manual manipulator and the item using the at least one image;

accessing item data comprising at least one characteristic of the item;

accessing constraint data relating to one or more of a robotic manipulator or the at least one characteristic of the item; and

generating at least one configuration of the robotic manipulator contacting the item based at least partially on one or more of the item data, the at least one image, or the constraint data, wherein the at least one configuration comprises:

one or more points of contact between the robotic manipulator and the item; and

one or more force vectors associated with at least a portion of the one or more points of contact.

6. The method of claim **5**, further comprising determining one or more force vectors applied by the manual manipulator to the item using one or more of: the at least one image, one or more sensors associated with the manual manipulator, or one or more sensors associated with the item.

7. The method of claim **5**, further comprising accessing force data indicative of the manual manipulator contacting the item,

wherein the at least one configuration is further based on the force data.

8. The method of claim **5**, wherein the constraint data relates to one or more of movement of the robotic manipulator or handling of the item, the method further comprising:

determining at least one constraint relating to the robotic manipulator using the constraint data; and

modifying the at least one configuration of the robotic manipulator using the at least one constraint.

9. The method of claim **5**, wherein generating the at least one configuration of the robotic manipulator comprises:

positioning the robotic manipulator relative to the item and a container configured to contain the item;

contacting one or more portions of the item with the robotic manipulator, wherein the one or more portions of the item correspond to the one or more points of contact of the at least one configuration;

applying one or more forces to at least a subset of the one or more portions of the item with the robotic manipulator, wherein the one or more forces correspond to the one or more force vectors of the at least one configuration;

moving the item relative to the container using the robotic manipulator;

determining an accuracy metric associated with movement of the item; and

modifying the at least one configuration based at least in part on the accuracy metric.

10. The method of claim **5**, wherein generating the at least one configuration of the robotic manipulator comprises:

generating a first configuration associated with one or more of: a first orientation of the item or a first location of the item; and

generating a second configuration associated with one or more of: a second orientation of the item or a second location of the item.

11. The method of claim **5**, further comprising:

determining a reference position of the item,

wherein the at least one configuration is further based on the reference position;

positioning the robotic manipulator relative to the item;

orienting one or more of: the item relative to the robotic manipulator or the robotic manipulator relative to the item, such that the item is positioned in the reference position relative to the robotic manipulator; and

contacting one or more portions of the item with the robotic manipulator, wherein the one or more portions of the item correspond to the one or more points of contact of the at least one configuration.

12. The method of claim **5**, further comprising:

accessing at least one additional image indicative of the item within a container configured to contain the item;

determining, using the at least one additional image, one or more of: a position of the item within the container relative to at least one additional object, an orientation of the item within the container, or a position of the at least one additional object within the container; and

determining at least one constraint relating to the robotic manipulator using the one or more of: the position of the item within the container relative to the at least one additional object, the orientation of the item within the container, or the position of the at least one additional object within the container,

wherein the at least one configuration is further based on the at least one constraint.

13. The method of claim **5**, further comprising:

receiving a request associated with placement of the item;

accessing location data corresponding to the item;

accessing at least one additional image indicative of the item within a container configured to contain the item;

determining, using the at least one additional image, one or more of: a position of the item within the container relative to at least one additional object, an orientation of the item within the container, or a position of the at least one additional object within the container;

determining at least one constraint relating to the robotic manipulator using the one or more of: the position of the item within the container relative to the at least one additional object, the orientation of the item within the container, or the position of the at least one additional object within the container; and

providing, to a device associated with a human operator, an indication of the at least one constraint.

14. A system comprising:

a non-transitory computer-readable medium storing computer-executable instructions; and

a hardware processor configured to execute the computer-executable instructions to:

receive a request associated with placement of an item;

access at least one image indicative of the item within a container configured to contain the item;

determine a position of the item relative to at least one additional object using the at least one image;

access at least one configuration for manipulation of the item by a robotic manipulator, wherein the at least one configuration comprises:

one or more points of contact between the robotic manipulator and the item; and

one or more force vectors associated with at least a portion of the one or more points of contact;

access constraint data relating to the robotic manipulator;

determine at least one constraint using the constraint data and the position of the item relative to the at least one additional object;

determine correspondence between the at least one configuration and the at least one constraint;

cause the robotic manipulator to contact one or more portions of the item, wherein the one or more portions of the item correspond to the one or more points of contact of the at least one configuration;

cause the robotic manipulator to apply one or more forces to at least a subset of the one or more portions of the item, wherein the one or more forces correspond to the one or more force vectors of the at least one configuration;

cause the robotic manipulator to move the item relative to the container; and

generate at least one additional image indicative of the container subsequent to movement of the item.

15. The system of claim **14**, wherein the at least one image indicative of the item within the container comprises one or more of:

an image of the container;

an image of the item; or

an image of the item within the container,

the system further comprising computer-executable instructions to:

position one or more of the container or the robotic manipulator relative to the other of the container or the robotic manipulator to enable the movement of the item by the robotic manipulator; and

determine the position of the item in the container using the at least one image indicative of the item within the container.

16. The system of claim 14, further comprising computer-executable instructions to:

access item data comprising at least one characteristic of the item;

determine a lack of correspondence between the at least one characteristic and the constraint data; and

provide, to a device associated with a human operator, an indication of the lack of correspondence between the at least one characteristic and the constraint data.

17. The system claim 14, further comprising computer-executable instructions to:

access one or more of:

at least one image indicative of a human operator contacting the item;

item data comprising at least one characteristic of the item; or

force data corresponding to one or more force vectors applied by the human operator to the item; and

generate the at least one configuration using the constraint data and the one or more of: the at least one image, the item data, or the force data.

18. The system of claim 14, further comprising computer-executable instructions to:

determine a location configured for access by the robotic manipulator; and

store the item in the location configured for access by the robotic manipulator.

19. The system of claim 14, further comprising computer-executable instructions to:

access a reference position of the item, wherein the at least one configuration is based at least partially on the reference position; and

orient the robotic manipulator relative to the item, such that the item is positioned in the reference position relative to the robotic manipulator.

20. The system of claim 14, further comprising computer-executable instructions to:

access a reference position of the item, wherein the at least one configuration is based at least partially on the reference position; and

use the robotic manipulator to move the item into the reference position.

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